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ARMSTRONG LABORATORY

DEVELOPING VIRTUAL INTERFACES FOR USE IN FUTURE FIGHTER AIRCRAFT COCKPITS (U)

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Kenneth R Boff

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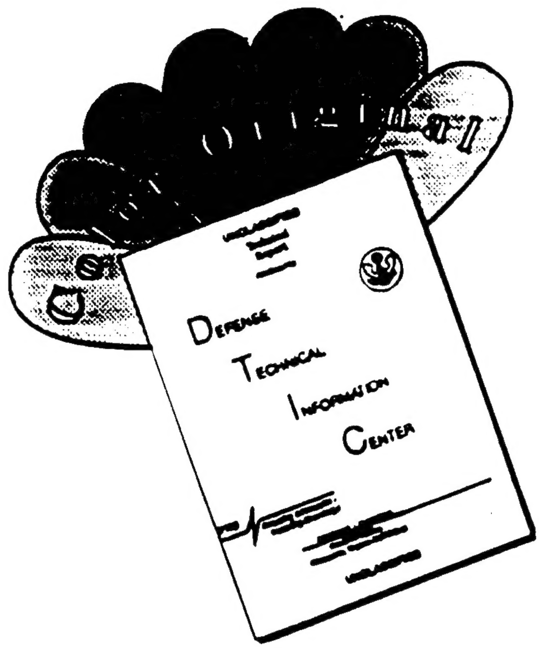

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13. ABSTRACT *(Maximum 200 words)*

The current research was conducted to evaluate the effect of employing multi-sensory displays for fighter aircraft cockpits on the performance of a simulated air combat task. Each of four experienced U.S. Air Force F-16 pilots flew twelve simulated missions which required them to locate and destroy four enemy bombers whose flight path was pre-programmed. Simultaneously, two other pilots were assigned to auxiliary cockpits in the laboratory and flew enemy fighter aircraft in an attempt to intercept and shoot down the primary pilot. Each pilot flew six trials using a cockpit comprised of conventional F-15 flight instruments and six trials using a modified, multi-sensory cockpit. The latter configuration included three-dimensional sound cueing information specifying the location of enemy aircraft, a head-slaved head-up display, a schematic representation of the terrain that provided pictorial information about self-motion and altitude, a spatial representation of the location of enemy and friendly aircraft in the vicinity, a pictorial representation of the status of aircraft weapons systems, and a multi-sensory Ground Collision Avoidance System. The results indicate that pilot performance and situational awareness were enhanced with the multi-sensory cockpit as opposed to the conventional cockpit. This report also contains a summary of the effects of changes in tactics and new control and display technology on the development of multi-sensory crewstations.

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EXECUTIVE SUMMARY

This report presents an overview of a research and development effort currently underway at the U.S. Air Force's Armstrong Laboratory at Wright-Patterson AFB, Ohio, to develop multi-sensory, virtually-augmented interfaces for future fighter cockpits. The fundamental premise underlying this effort is that multi-sensory interfaces can optimize pilot workload, situation awareness, and overall air combat performance by taking advantage of the parallel information extraction capabilities of the various sensory modalities, and by presenting critical information in an intuitive and readily comprehensible manner. Toward this end, the Armstrong Laboratory's Fusion Interfaces for Tactical Environments (FITE) Facility is currently developing interface concepts that combine visual, auditory, and haptic information to enhance pilot performance. This report provides an overview of this effort, including a discussion of the effects of changing tactics and emerging technologies.

FOREWORD

The work described herein was performed by members of the Human Interface Technology Branch, Human Engineering Division, Crew Systems Directorate, Armstrong Laboratory (AL/CFHP), Wright-Patterson Air Force Base, Ohio. The experiment was conducted in the Fusion Interfaces for Tactical Environments (FITE) Laboratory. The authors would like to thank David Snyder, Ken Aldrich, Liem Lu, Mark Visconti, and Michael Poole of Logicon Technical Services, Inc. for providing essential software and hardware support throughout all phases of this investigation; Major Julie Cohen for reviewing and editing earlier drafts of the document; and the fighter pilots for their tireless participation during the interface evaluation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF COLOR PLATES

LIST OF TABLES

LIST OF APPENDICES

1.0 INTRODUCTION

There are two major purposes of this report. The first is to present the rationale and general plan for a program of human factors engineering research related to the development of virtual environment technology for advanced crewstation interface designs. Specifically, this program will support the development and implementation of multi-sensory virtual interfaces for future U.S. Air Force crewstations, and will be conducted in the U.S. Air Force Armstrong Laboratory's Fusion Interfaces for Tactical Environments (FITE) Laboratory at Wright-Patterson Air Force Base, Ohio. The FITE Laboratory is contained within the Crew Systems Directorate, also located at Wright-Patterson AFB. This effort will also support the US/French Memorandum of Understanding Regarding the Cooperative Development and Evaluation of Super Cockpit Technologies. The other major purpose of the current report is to document an experiment that represents the initial empirical effort in this process. This experiment was designed to assess the effects of a modified F-16 cockpit display configuration on pilot performance of an air-to-air combat task. The modified cockpit consisted of a number of virtual interfaces that included visual and auditory displays (described in more detail below) designed to enhance pilot situation awareness and overall task performance.

The research program discussed in this report has been designed to operate in parallel with a related program of engineering development within the FITE Laboratory. These two areas of emphasis are intended to interact to ensure that the final technical products of the program (i.e., virtual interfaces that will enhance pilot performance in operational tasks) will represent state-of-the-art technology which also affords effective use by the pilot. Specifically, the development of prototype virtual interfaces and new technical approaches to human-machine interface design will inevitably lead to the identification of human factors research issues. The results of all human factors research will then feed back into the engineering design cycle to provide guidelines for the continued development and eventual implementation of these interfaces.

Incorporating virtual environment technology into the design of future crewstation interfaces may offer a number of significant human performance advantages. The nature of a fighter pilot's mission can often place very high demands on perceptual, cognitive, and physiological capabilities, particularly in high workload situations. Rapid and reliable acquisition of information about the status of weapons systems, other aircraft and targets in the area, and the maintenance of spatial orientation are all key to the success of a mission. Awareness of these and other critical aspects of the air combat mission may be substantially enhanced using virtual environment technology.

The goal of our research program is to provide relevant human factors engineering knowledge to aid in the design of these interfaces. While one major goal of the laboratory is the development of virtual interfaces for fighter aircraft cockpits, our intent is to pursue a program of research that has relevance to other applications of this

technology. Virtual environments are potentially useful in many areas of human endeavor, and our efforts to generate a relevant human factors database, to develop experimental paradigms for investigating human performance in virtual environments, and to generate models of human performance in such environments should prove useful in these other applications.

1.1 Virtual Interface Development and Evaluation

The development and evaluation of virtual interfaces presents a unique problem in that it is difficult to evaluate the attributes of multi-sensory virtual displays without experiencing them within the application context. In many cases, what seems to be a valid display or control concept breaks down when it is experienced. For this reason, multi-sensory virtual-interface creation, integration, and evaluation can best be accomplished within a rapidly re-configurable prototyping and simulation facility which can create a virtually-augmented environment for the observer. Exploratory development of multi-sensory virtual-interface technologies for tactical cockpits is currently being performed in the Fusion Interfaces for Tactical Environments (FITE) Laboratory (see Figure 1).

The term "fusion interfaces" is used to describe a class of interface concepts which utilize both virtual and non-virtual concepts and devices, integrating information presented to the visual, auditory, and haptic modalities. Another description for a fusion interface is a multi-sensory virtually-augmented interface. The FITE facility is a specialized flight simulator which allows the rapid and efficient development of fusion concepts through direct experience, as well as the evaluation of fusion concepts by operational fighter pilots. The facility is utilized by a multi-disciplinary team composed of operational pilots, human factors engineers, electronics engineers, optical engineers, computer scientists, and experimental psychologists.

1.2 Development Process within the FITE Laboratory

The products of the FITE Laboratory are the multi-sensory virtual-interface concepts themselves, the evaluations of the interface concepts, and the identification of basic research topics to be pursued in more controlled experimental settings. As a tool supporting development, the FITE Laboratory operates in three main cycles. These cycles are depicted in Figure 2. The three cycles consist of: (1) the inner loop, which represents the creative process and which enables the rapid creation and initial evaluation of concepts, (2) the basic research loop, which outputs basic research topics to other facilities and inputs results back to the interface design process, and, (3) the evaluation loop, which involves evaluation of complex aspects of human performance in experimental situations with high operational relevance.

Figure 1. Photograph of the Fusion Interfaces for Tactical Environments (FITE) Laboratory

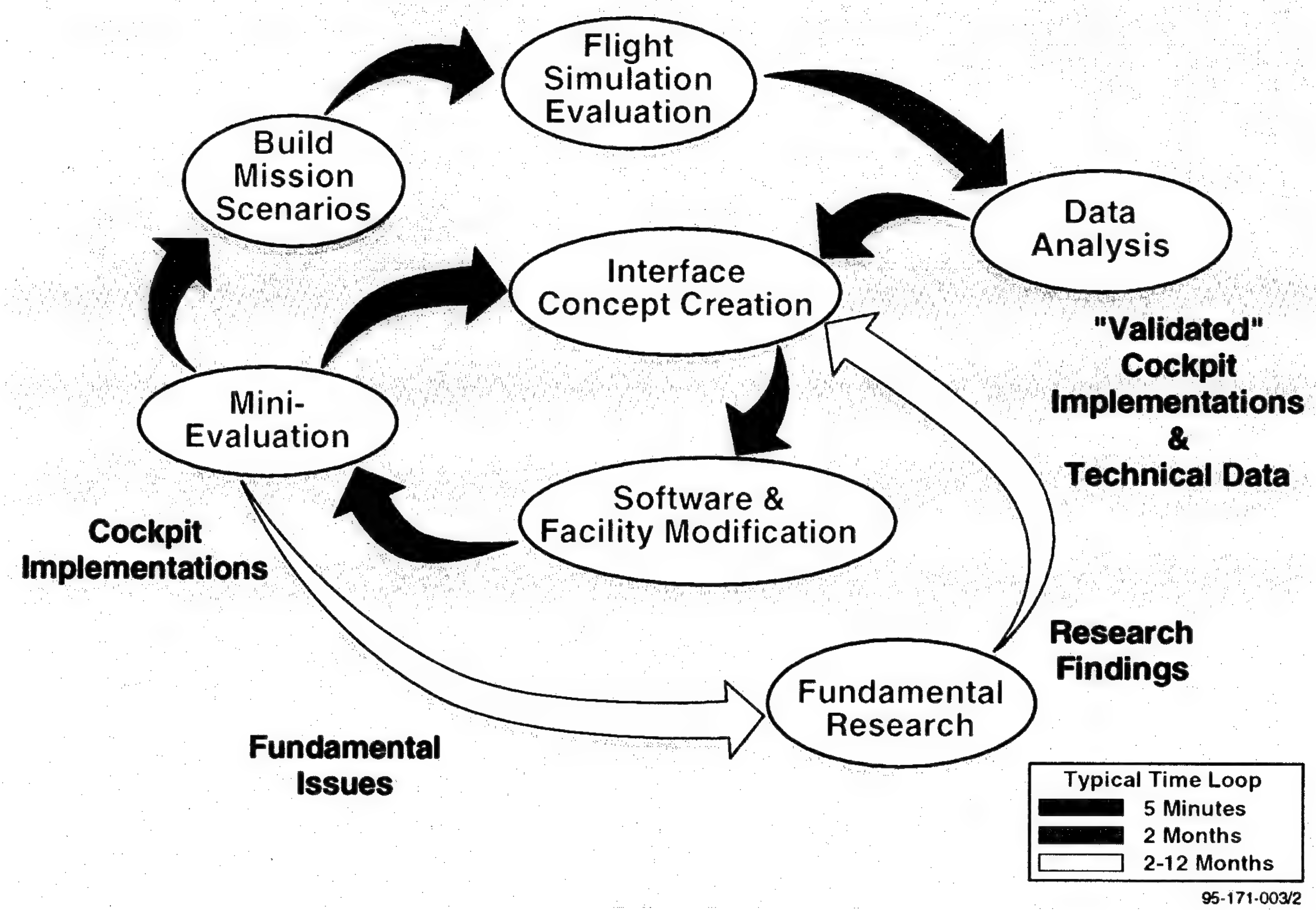


Figure 2. Schematic of the development cycles within the FITE Laboratory

1.3 The Development of Virtual Environments

Virtual environment technology represents an approach to the design of human-machine interfaces that attempts to facilitate the exchange of information and control between a human operator and a technical system. Its principal means of accomplishing this is to provide highly salient multisensory perceptual information (i.e., that which effectively attracts and maintains the attention of the user) and which communicates information about the results of control inputs and the overall status of the system in as intuitive a manner as possible.

The relation between the human user and a technical system, as mediated by a human-machine interface, is symbolically represented in Figure 3. The human operates on the system by executing some form of control activity (e.g., manual control, voice-activated control, etc.). If operating properly, the system accepts this control input and responds accordingly. A well-designed interface will facilitate the execution of this control input, and will then provide information to the user in the form of readily perceivable and comprehensible feedback about the immediate result of the control action as well as the overall status of the system. This process can be characterized as an ongoing cycle of perception and action, and the key site of exchange of control and information is the human-machine interface. There are two major components to a virtual interface, both of which must be present for the interface to exist, the control/display hardware, and the user. The display and control hardware which produces the multi-sensory stimulation for the user is generically referred to as the virtual environment generator. A generic virtual environment generator can best be described by drawing an analogy with a computer graphics system. In fact, the traditional elements comprising a graphics system also comprise a virtual visual environment system. There is an image generator, an image transducer, a display, and finally a control mechanism for user feedback into the generator. The difference between a virtual visual environment generator and a conventional visual environment generator is in the display itself. The display in a virtual generator is a virtual device. Environment generators for the other human senses are comprised of similar functional blocks, with the display, transducer, and control taking different forms. Typically, the image generator, whatever the sense modality, creates the initial image electronically, the transducer transforms the electronic image into a format useful for the display, which creates energy which can be sensed directly by the human, such as light, sound, or force. Figure 4 illustrates these relationships in a diagrammatic form.

Research in the design of human-machine interfaces over the course of several decades has aided the development of displays and controls whose properties can minimize demands on users' perceptual, cognitive, and physiological capabilities. These may range from information extraction processes related to visual and auditory perception, or information processing, decision making, and problem solving skills. Facilitation of control processes can be accomplished by taking account of human psycho-motor behavior and skills in the design of the interface.

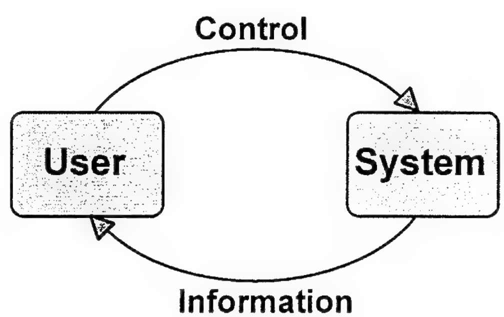


Figure 3. Schematic Model of Human-Machine System and Interface.

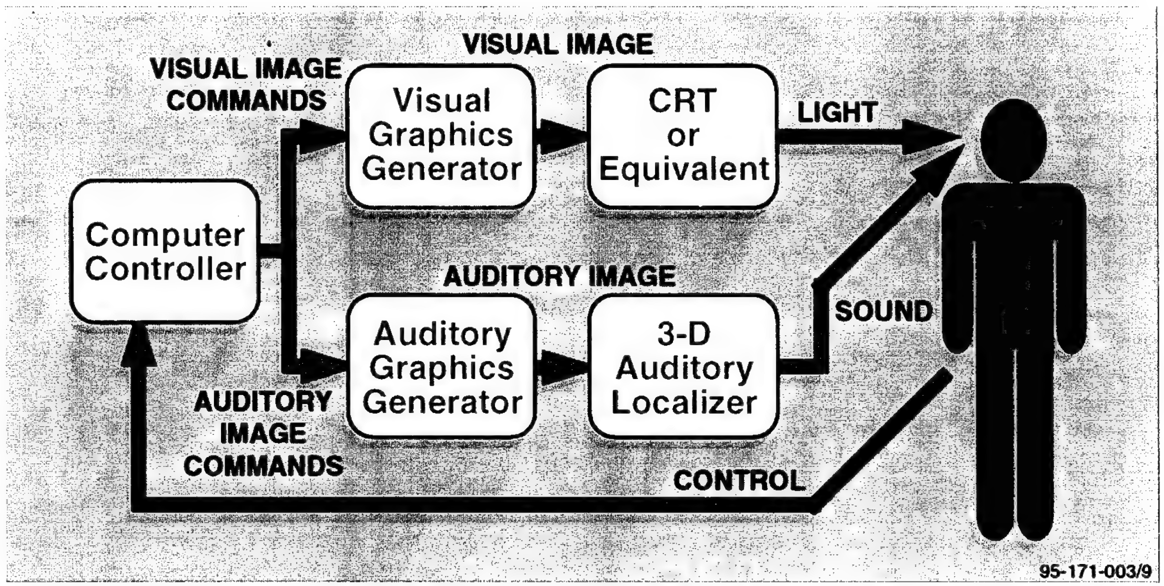


Figure 4. Diagram presenting relationships between image generation and display.

Developments in virtual environment technology have been strongly related to progress in the design of human-computer interfaces (Card, Moran, & Newell, 1983; Ellis, 1991). Early computer systems required that users' control and information extraction activities be mediated by relatively low level, abstract computer languages. This generally required a great deal of learning and/or continuous effort on the part of the user. Later generation systems adopted the "desk-top metaphor" as a basis for interface design. In systems of this type users interact with the computer by means of a more intuitively symbolic interface in which visual icons and auditory "earcons" provide information about human-computer activities. Ellis (1991) argues that virtual interfaces represent a further development in this evolutionary process. Virtual interfaces provide information about system control and status in a multisensory, intuitive fashion that takes advantage of several key technical advances in computer science and information display technology.

The development of virtual environments has been principally driven by two factors:

(1) Technical developments in computer graphics hardware and software, visual and auditory display technology, and methods for measuring human body motion in real time and using it as input to a computer, and

(2) An increased awareness of the importance of designing interfaces that take maximal advantage of human perceptual and cognitive capabilities.

The goal of this technology is to design and implement computer-generated environments that are representations of real, potentially real, or in some cases imaginary environments. Virtual environments can consist of visual representations of realistic terrain and objects that are not patterned after any corresponding or identical existing terrain or objects, as is often the case with current flight simulators. Virtual environments can also consist of synthetic representations of objects and events that are directly sensed from the real environment. Our research efforts in general are concerned with this latter type of virtual environment. We are interested in developing virtual interfaces that will make available information specifying the physical and tactical "environment" in which the pilot finds himself in as perceptually and cognitively salient a fashion as possible. The experiment described in Section 5.0 of this report represents an initial attempt at developing the means for making this type of information available to a pilot.

1.4 Progress in Virtual Environment Technology

Much of the progress in virtual environment technology has been driven by advances in three areas: (1) computer graphics hardware and software, (2) multisensory displays, and (3) input devices sensitive to body movements.

1.4.1 Computer Graphics.

The virtual visual interface is composed of a visual image generator and a visual image portrayal system. The visual image generator can be a computer graphics system, an imaging camera, or another similar sensor. Of the three principal modalities currently targeted by virtual environment systems (visual, auditory, and haptic), the technology for visual applications is the most mature. This is fortunate in that some estimates of information processing by humans list vision as typically being used for 80% of information input. This fact makes computer graphics, sensor technology, and image portrayal mechanisms the most important technology for the creation of robust and high-fidelity virtual environments. Image portrayal technologies involved in the transformation of electronic-formatted imagery to a visual format include miniature cathode-ray tubes, liquid crystal displays, optics, and interface electronics. Many of these technologies are being considered for incorporation, or are already integrated, into the aircraft cockpits. These include Head Up Displays (HUDs), and helmet-mounted displays (HMDs), as well as three-dimensional panel mounted displays. Virtual visual controls include helmet-mounted head position/attitude trackers and eye line-of-sight trackers.

Recent developments in the area of computer graphics with relevance to virtual environment technology include complex computer image generation systems with the capability of producing highly realistic visual representations of synthetic environments. The ability to represent the behavior of multiple actors (either in real time or as programmed) in a virtual space in real-time has also been particularly critical in the development of virtual environments.

High fidelity representations of multiple actors and objects in a virtual environment requires powerful graphics engines to perform many high level calculations at rapid speeds. While developments continue in this area, what has been accomplished to date has made initial research and development in virtual environments possible.

1.4.2 Multisensory Displays.

The technology to totally emulate naturally occurring environments within a virtual environment does not exist at this time. However, devices enabling the creation of a limited virtual experience do exist. HMDs, helmet-mounted head, hand, and eye line-of-sight trackers, three dimensional auditory displays, and tactile stimulation devices have been developed and evaluated by several academic, industrial, and military institutions in a non-integrated, context independent, fashion since the mid 1960s (c.f., Vickers, 1970; Haas, 1984; Foley, 1987).

Visual displays. Visual displays for virtual environments include HMDs, boom-mounted displays, projected surfaces, and monitor-based displays. HMDs are particularly useful in providing a user with an impression of full immersion in a virtual environment. Full immersion refers to the impression that one is effectively surrounded with virtual imagery.

In an HMD, observers can experience an unlimited "field of regard" similar in expanse to that which is available in the real environment. In other words, the size of the visual field that can potentially be viewed with a series of head movements is effectively unlimited. The size of the instantaneous "field of view" is constrained in an HMD by the characteristics of its optics in a manner similar to the physiological constraints placed on field of view in normal perceiving. However, through the use of head-trackers it is possible to calculate the orientation of the head in virtual space and provide an appropriate visual display. Therefore, it is possible to sample the entire visual field by making head movements and, in some applications, eye movements.

Auditory displays. Virtual auditory displays have been developed which utilize three-dimensional auditory localizers combined with audio image sources and stereo headsets. The three-dimensional auditory localizer samples the auditory image, created by an audio image source such as an intercom or computer generated tone source, digitally filters the signal based on a head-related transfer function (Wenzel, 1992), which is a function of sound localization in azimuth, elevation, and range, and results in a left and right audio pair. The audio pair is converted to an analogue form and displayed over a stereo headset.

The ability to represent hi-fidelity, three-dimensional auditory information has improved greatly in recent years. Recent studies of auditory signal localization have been significantly aided by the development of three-dimensional auditory displays (e.g., Begault & Wenzel, 1992; Fisher, Wenzel, Coler, & McGreevy, 1988; Wenzel, 1992). The addition of high fidelity auditory signals with three-dimensional characteristics to virtual environments can greatly enhance the multisensory nature of this technology, as well as significantly enhancing the sense of immersion. It also offers a number of interesting possibilities for the presentation of information in virtual environments. For example, it has been noted the "the function of the ears is to point the eyes" (Wenzel, 1992, p.81) - in other words, audition can serve an alerting function and direct the more spatially acute sense of vision in the direction of an important source of information. This suggests that one of the functions of auditory information in the real environment that could be used to advantage in a virtual environment is to provide information about critical events that are outside of the current field of view.

Haptic displays. The development of haptic displays for virtual environment technology is also currently being explored (e.g., Monkman, 1992). These displays, which enable the user to sample virtual tactual and kinesthetic information are less developed technologies, but may be made available for use as current research advances. Control loaders, typically utilized in flight simulation to accurately model the stick feel of a particular aircraft, also fall into this category but are a mature technology.

Haptic displays may be particularly useful in providing information about the presence of dynamic forces operating within a human-machine system (Burdea, Zhuang, Roskos, Silver, & Langrana, 1992). Its use, in combination with visual and auditory information, should provide the user with a more holistic impression of system activity

than is possible with visual and/or auditory information alone. However, the degree to which haptic information can aid human performance in complex systems, and the types of environmental and/or system information that can best be conveyed by haptic information are still open questions for the research community.

1.4.3 Input Devices.

Technical developments in this area include devices for the detection of users' head, eye, hand, and other body movements. The acquisition of these signals permits the host computer to calculate the user's pattern of body motion (position, velocity, and acceleration) which in turn permits the calculation of appropriately updated information on the visual, auditory, and/or haptic displays. For instance, a 30 degree rotation of the head to the left can be detected as such by means of a head-tracker. This signal is then used as input for the computer image generation system which calculates an appropriately transformed visual, auditory, or haptic display. The development and refinement of body motion sensors is another area of ongoing technical development whose outcome is expected to be an enhanced sense of realism and flexibility in the use of these systems (e.g., So & Griffin, 1992).

Some virtual environment systems possess noticeable temporal delays between movements of the head (for instance) and updating of the visual imagery. This can occur in situations in which the host computer's capability is insufficient to simultaneously process information about the location of the head while also processing a new visual display. This is particularly true in situations where the visual display contains high levels of detail, which requires greater computational capability. Among the possible effects of these spatio-temporal disruptions are adverse effects on user performance and/or symptoms resembling motion sickness (Hettinger & Riccio, 1993). Research and development in this area is concerned with enhancing the computational capabilities of host computer systems, as well as developing body motion prediction algorithms to provide feedforward information to the host about future body position.

The existence of input devices driven by body movements allows for a close modeling of real world perception-action couplings. Head movements, for instance, in the real world have important consequences in terms of producing transformations in the optic array which accompany the motion and which specify its characteristics, such as velocity and extent. These transformations are informative not only about the environment, but also about the relation of the perceiver to the environment. By making this type of interaction possible in a virtual environment we can more accurately reproduce conditions of normal perceiving.

1.5 Applications of Virtual Environment Technology

There are many areas of education, science, and entertainment that stand to benefit from the development of virtual environment technology (National Science Foundation, 1992). Subsequently, there is widespread interest in this technology in many

sectors of society. The commercial application of virtual environments has been identified by several industrial corporations, such as Autodesk, Sense8, Vermont Microsystems, and Dataquest in the United States (Hindus, 1990) as well as Matsushita Electric works in Japan, Satra Footwear Technologies and W-Systems in England, and Art + Com in Germany (Emmett, 1992).

For the most part, current applications are to be found in the entertainment industry and the military, although there is a large and growing interest in medical applications of virtual environment technology. In the case of entertainment applications, the capability to produce illusory sensations of motion and action in a virtual environment appears to be very appealing to consumers. Therefore, most examples of virtual environments in this context concentrate on producing compelling illusions of "presence," the sensation of being immersed in a synthetic, yet realistic, environment.

In the military, most applications of virtual environments have been geared toward training. Flight simulation has been employed for years as a means for training student pilots by providing interactive, computer-generated visual, auditory, and haptic information. Other military applications that are foreseen include mission rehearsal, large-scale interactive simulation in which users from physically remote sites share a common virtual space, visualization of complex databases, and advanced computer assisted design.

One area in which virtual environment technology may prove to be a great benefit is in the design of cockpit interfaces for future fighter aircraft. The characteristics of high performance air-to-air and air-to-ground tactical missions place great demands on pilots' perceptual, cognitive, and physiological capabilities. Virtual interfaces, through their use of multisensory sources of highly intuitive perceptual information, can offer significant performance advantages by reducing pilots' overall workload, enhancing their situation awareness, and helping to prevent loss of spatial orientation.

Future tactical aircraft will be operating in a much more demanding environment then they do today. The lethality of weapons systems continues to increase. The proliferation of advanced weapon technologies such as directed energy weapons, reduced target delectability, and increasing use of passive sensor methods will create increased air combat dynamics as well as requiring additional time critical decisions to be made by the pilots of future tactical aircraft. This will place tactical aircraft pilots in more difficult mission environments than they currently experience. To counter the increasingly complex tactical environment, advanced pilot-vehicle interface techniques, which enable a more efficient use of the pilot's abilities are required to be developed and employed, thus providing greater situation awareness, enhanced controllability of the overall weapon system, increased lethality, and increased survivability. These factors, in turn, combine to enhance weapon system effectiveness. Anticipated trends in the evolution of cockpits of the future are discussed in the next section of this report.

However, the cockpit is not the only environment in which advanced interfaces may increase the performance of a total system. The link, or interface, between man and intelligent machine, may be limiting the productivity and efficiency obtainable through automation and machine intelligence (Foley, 1987). The challenges involved in linking humans and intelligent machines are increasing due to increased computational power, increased availability, increased machine-to-machine communication capability, increased functional capability through higher level languages, and increased memory capacity.

2.0 THE COCKPIT OF THE FUTURE

The fighter cockpit is the pilot's interface with the aircraft, its weapons systems and the outside world. In turn, it is the combination of all these factors that determines the form of effective air-combat tactics. Therefore, it is imperative that the designers of cockpits for future fighter aircraft understand and consider the implications of technology and fighter tactics on the pilot and the tactical environment.

In order to predict the tactical environment of the future fighter pilot and the implications for cockpit design, it is first necessary to review briefly past technological progress in the field of air combat. Over the course of air-combat history, advances in technological capabilities have often had significant influence on the tactics employed and the success of those tactics. Fighter pilots are a resourceful lot, always seeking to gain advantage by exploiting superior capabilities where available, and at the same time tailoring tactics to minimize the impact of any technological advantages of the enemy. This influence is so strong that it often can be said that technology drives tactics. It should be remembered, however, that technology is a two-way street; the threat must also be considered when developing tactics. Seldom can a weapon system be employed effectively in an optimum manner with total disregard of threat capabilities. These factors must be considered when predicting the effectiveness of any postulated capabilities upgrade, since the application of new technologies in obsolete tactical environments inevitably leads to incorrect and misleading projections.

2.1 Historical Trends

In the early days of air combat, hand signals, aircraft motion signals, and sometimes signal flares were the only practical means of communication between pilots, and the eyeball was the only available sensor. Mercifully, short-range guns were also the most lethal air-to-air weapon. Consequently, effective tactics depended on relatively close formations, both for offensive coordination and defensive mutual support. Visual range was the limit, but normally formations were much tighter because of the need to support wingmen quickly with short-range gun firepower.

Since the most lethal threat axis was at the rear of the formation, line-abreast and echelon formations were preferable, with echelon lending maximum flexibility in offensive maneuvering and line abreast providing optimal visual coverage of the rear of the formation. Aircraft speed is another important factor in tactical formations, largely because of its dominant influence on turn radius. Maintaining echelon formations becomes increasingly more difficult as aircraft spacing approaches the equivalent of the aircraft turn radius. All these factors combined to constrain element formations to about 50 ft to 300 ft until the late 1930s.

The introduction of reliable two-way radios in fighters shortly before World War II led to wider separations between aircraft, with defensive formations trending toward near line-abreast with 500-1000 ft separation (limited by effective gun range), and offensive formations typically 200-500 ft echelon (limited by turn radius). The radio also allowed better offensive coordination and wider separations between elements in larger formations,
while defense was coordinated within individual elements. As speeds increased with the jet age and greater effective firing ranges were obtained through larger gun calibers, higher firing rates, and more effective gunsights, formation separations increased accordingly.

Several technological breakthroughs occurred at about the same time, in the late 1950s. These included supersonic cruising speeds, fighter radars, and guided missiles. The initial tactical response to these innovations, in the absence of corroborating air-combat experience, was a tendency to discount the probability of maneuvering air combat and to rely on single, or widely separated coordinated independent interceptors to counter the perceived high-altitude strategic bomber threat with Beyond-Visual-Range (BVR) missiles. Renewed exposure to air combat during the 1960s, particularly in Vietnam and the Middle East, however, demonstrated that the dogfight was not dead and that the widely accepted tactics of the time were not effective in fighter-vs-fighter combat. In addition, surface-to-air missiles (SAMs) were shown to be as great a threat as enemy fighters.

Dependence on radar, both by fighters and SAMs, quickly reversed the long-established trend toward increasing combat cruise and engagement altitudes. Typical cruising altitudes dropped from the 30,000-40,000 ft range prevalent since World War II down to near ground level. Such low altitudes limited the effectiveness of SAM and Ground-Controlled Intercept (GCI) radar detection and tracking, and, with the pulse radars of the day, the lower fighter generally had a detection advantage with airborne radar. Further combat experience, however, demonstrated that very low altitudes contributed to higher losses from ground fire, so altitudes were sometimes increased somewhat as a compromise, depending on the perceived level of threat from various hostile defenses.

Recognition of the continued threat from enemy fighters and the new threat from SAMs renewed reliance on visual formations for both defensive mutual support and offensive maneuvering. In addition, the poor reliability of early fighter radars and long-range radar missiles contributed to greater reliance on visual support and short-range missiles with infrared (IR) guidance. These weapons typically had minimum-range limits on the order of a few thousand feet, maximum ranges of 1-2 NM, and were limited to launches from the target's rear hemisphere. The eventual effect of these factors, as well as larger aircraft size and reduced maneuverability, was an increase in element formation spacing. Offensive element formations typically ranged from 1-3 NM near line-abreast, with defensive formations tending closer to 3,000-9,000 ft echelon or line-abreast. Also the increased range of even short-range missiles over guns led to a deemphasis on

echelon formations for defense, since such arrangements offered less visual protection to either a leader or wingman against longer range weapons fired from the rear quarter of the formation.

By the 1970s, technology again had an impact on fighter tactics. This time developments were more evolutionary in nature, with all-aspect air-to-air weapons and sensors becoming increasingly more reliable and lethal, largely as a result of solid-state electronics. More effective weapons tend to drive optimal tactics toward the offensive end of the spectrum in an effort to ensure being first with an opportunity to employ deadly ordnance, while denying the enemy that same opportunity. In other words, the more lethal the weapons involved, the more valid is the premise that, "A good offense is the best defense." This factor has been reflected in looser, more offensive maneuvering fighter tactics, and a further reduction in the usefulness of echelon, or "Fighting Wing" offensive maneuvering in which a leader and the wingman maneuver as a single entity. Offensively, an increase in the number of maneuvering entities generally improves the probability that one entity will achieve a lethal position versus the enemy, while at the same time generally decreasing the time required. It also could be argued that greater separations within visual range can be more effective for detecting threats to one's wingman, especially when those threats can come from any direction. In addition, wider separations reduce the probability that all friendly fighters will be detected visually by the enemy.

Another effect of advancing technology in recent years has been improved fighter look-down/shoot-down capability. Doppler radars have largely removed the low-altitude sanctuary against radar guided weapons. In addition, there has been a proliferation in recent years of highly lethal short-range, low-altitude SAMs that has greatly reduced the desirability of operating at low levels. Consequently, there has been a renewed trend toward higher combat cruise and engagement altitudes, while relying on electronic countermeasures (ECM) and active suppression for defense against the numerically inferior high-altitude SAMs. This trend was quite apparent in the recent Gulf War. Even air-to-ground combat, traditionally a low-altitude activity, has begun to move to higher altitudes due to these factors and the increased delivery accuracy obtainable through the employment of guided weapons.

Cockpit designers for the next generation of fighter aircraft will have to consider the impact of a number of new and emerging technologies. The most important of these, and their implications for cockpit design, are outlined below.

2.2 Supercruise

"Supercruise" is the ability to cruise at supersonic speeds without the use of fuel-inefficient afterburners. History has shown that fighter pilots will generally choose to fly at the highest practical airspeed available to them in combat situations. One of the strongest reasons for this is the dominant self-preservation motive. High airspeed

normally reduces the time of exposure in hostile airspace and makes effective interception by enemy fighters more difficult, especially when concern is primarily for the historically-dominant air-to-air weapons that are restricted to rear-hemisphere employment. When the newer all-aspect weapons are considered, the defensive advantages of high speed are less obvious, since forward hemisphere vulnerable envelopes are normally expanded by target speed. Even here, however, speed facilitates avoidance of effective interception by the use of course changes, since the vulnerable envelope changes more rapidly with target aspect at higher speeds. A substantial speed advantage may allow a target literally to "end-run" around an opponent, or aerodynamically defeat a deployed weapon, even if that weapon is fired from the forward hemisphere. In addition, the kinetic energy inherent in high speeds allows a pilot more energy maneuverability options, as that speed may be converted to higher altitudes for either offensive or defensive purposes. The offensive value of higher airspeeds is similarly positive, as weapons envelopes are typically expanded, and target interception is facilitated.

Since supercruise is most effective and practical at higher altitudes (above 30,000 ft), this capability will favor operation at these higher levels. Unfortunately, this is precisely the level at which contrails are most often encountered. Because pulling a contrail can negate billions of dollars in stealth design, there will be a push toward even higher altitudes in an attempt to operate above the contrail level. This factor, in turn, will necessitate increased emphasis on crew survivability and physiology. Research into the practicality of contrail suppression is also in order. When operating above the contrail level is not practical, pilots will tend to cruise slightly below that critical altitude, with the attendant performance and efficiency penalties. Complications with contrails will also tend to promote increased operation at night and in poor visibility when contrails are less apparent.

2.3 Low-Observable Considerations

Another likely technology applicable to next-generation fighter aircraft is some measure of low-observability (LO), or "stealth." Because of the current high cost of this technology the degree of reliance on stealth capabilities will vary widely with the intended mission of the particular fighter and its position in the "high-low mix" of combat aircraft. It can be assumed, however, that some measure of LO capability will be a feature of any new fighter design. Since LO, in general, only delays enemy sensor detection until a somewhat closer range than would otherwise be the case, and the effectiveness of LO measures is generally highly dependent on the aspect of the target relative to the sensor, eventually the pilot on an LO aircraft can expect to be detected at shorter range. Therefore, it is at medium and long ranges that tactics will be most affected. Under these circumstances standoff range and aspect become critical factors.

Because LO effects can be very complex, and aspect control in combat conditions can be extremely limiting, it is probable that pilots will take the approach of simply attempting to avoid the aspects that result in MAXIMUM signature, rather than trying to achieve their MINIMUM signatures. Even this approach limits the pilot's maneuvering options and increases workload, since the pilot now has to be more concerned about his aspect than would be the case in a conventional fighter. Cockpit display designers should consider this factor and devise means to facilitate signature control through aspect.

Specialized tactics will also evolve to take greater advantage of LO capability. One likely result is an increased prevalence of multiple-axis attacks. In this case, one fighter (or element), the decoy, conducts a conventional offset intercept without regard to signature control (or possibly even maximizing signature to ensure detection), while a second fighter (or element), the shooter, controls intercept geometry for minimum signature. The decoy can continue to press the attack if conditions are favorable, or abort as necessary, while the shooter closes to firing range, hopefully undetected.

A second tactic facilitated by LO capability is the "cooperative launch" in which one fighter (or element), the illuminator, actively tracks the target at a safe distance, while another fighter (or element) using passive LO techniques, the shooter, closes to weapons range on the target undetected. The shooter may rely on the illuminator (via datalink) for target tracking, identification, and weapons guidance for semi-active radar missiles or for active weapons prior to their active guidance phase.

LO capability will also have tactical implications in the air-to-ground arena. Because surveillance and acquisition radars are generally widespread in hostile airspace, it may be difficult for a LO fighter avoid enemy detection altogether in the target area, since the locations of some sensors will inevitably be such that the LO effects are minimized. However, detection by a given site might be minimized by aspect control, and high altitude may reduce the range of most enemy ground-based sensors. These factors may promote greater emphasis on high-altitude attacks, as opposed to the more prevalent current tactics which employ a low-altitude ingress to a pop-up, followed by a diving delivery. Stand-off precision weapons will also complement LO capability. These weapons, which include laser-guided bombs (LGBs) and inertially aided munitions (IAMs) as well as self-propelled "smart" weapons, might allow the attacking LO fighter to remain outside detection range during most, if not all, of the approach and delivery, then to quickly withdraw out of range after releasing its weapons.

"Smart" weapons may be employed using low-altitude, "lofting" attacks, such as those common today. High-altitude attacks with free-fall weapons may also be compatible with LO capability, particularly low-to-high LO. One complication, however, is that the required delivery angle for ballistic ordnance is relatively steep from higher altitudes. If steep diving deliveries, which tend to bring the bomber to lower, more dangerous altitudes, are to be avoided, specialized aiming devices will be necessary for visual bombing. Typical Head-Up Displays (HUDs), for example, are limited in the

depression angle that may be displayed. Here, depression angle is defined as the angle between the aircraft's fuselage reference line (essentially the fuselage longitudinal axis) and the aiming reference (bomb pipper). If too great a depression is required at release, reduced accuracy will result. Since the required depression angle at release is, in general, inversely related to dive angle at a given altitude above the target, this factor could limit the minimum acceptable delivery angle and, therefore, the maximum LO effectiveness for high-altitude deliveries. New displays and sensor arrangements would facilitate high-altitude level, or shallow "bunt" deliveries, which may allow the pilot more optimization of LO capabilities, as is currently the case with the F-117 fighter.

2.4 Air-to-Air Datalink Considerations

Air-to-air datalink has a very high potential for altering tactics, especially in the air-to-air arena, by contributing to improved situation awareness (SA) and an increase in the range of effective mutual support. In general, improved SA results in a trend toward emphasizing offense, as opposed to defense. If pilots are confident they understand the tactical situation, perceive no immediate threat to their own forces, and can rely on adequate warning of any new threats, they are free to concentrate on optimizing their offensive posture. Reliable air-to-air datalink, the Joint Tactical Information Data System (JTIDS), and a comprehensive network of linked ground-, air-, and space-based sensor and intelligence platforms can contribute greatly to enhanced SA.

Similarly, such a system offers the first opportunity in the history of air combat for exploiting a primary defensive sensor system both more reliable and more capable than the human eye. To date, primary fighter electronic sensors have been most severely limited in their field of regard (FOR). So while they might have range capabilities superior to the human eye, at the relatively close lethal ranges of air-to-air weapons the pilots' vision, with shorter range but larger FOR, often provided a better probability of detecting the enemy. Particularly for rear-hemisphere threats, visual mutual support coordinated by voice radio has historically proven to be the most effective defensive strategy.

With the availability of reliable air-to-air datalink, it will be possible to coordinate electronic sensors among large numbers of friendly fighters as well as support assets to provide dependable 360 degree electronic sensor mutual support, analogous, but in many ways superior, to current visual mutual support. Therefore, there is some possibility that, after an initial period of evaluation and experience to build confidence, the doctrine of almost total reliance on visual mutual support may at last come to an end. Dependability and reliability of such a system are crucial, however. If pilots are not convinced of its dependability, tactics dependent upon this capability will not be developed; visual mutual support will continue to be the norm, and most of the advantages of this capability will be lost.

Although it is unlikely in the foreseeable future that visual mutual support doctrine will be totally abandoned, we can expect a trend in that direction when circumstances are favorable. This trend should be reflected in an increased willingness to employ coordinated autonomous fighters in an air-to-air environment well covered by linked sensors. Such autonomous operations are one method of enhancing offensive effectiveness through the mechanism of increasing the number of separate maneuvering entities on the friendly side of the air-to-air engagement.

Even with practical electronic mutual support, the pilots' vision continues to provide an additional valuable sensor capability, so, when environmental and tactical conditions permit, it can be expected that conventional, visual-support-based tactics will continue to be employed in many scenarios, with possibly minor modifications to enhance the contribution of electronic mutual support. One of the primary limitations of visual mutual support is its ineffectiveness at night and in poor visibility. In these situations, fighters currently must rely on very close formations, which restrict maneuverability and both offensive and defensive effectiveness, or adopt trail formations, using electronic sensors to maintain position. Air-to-air datalink should remove the necessity of the former, and improve the effectiveness of the latter tactic. Although air-to-air datalink should improve pilot SA and effectiveness in day/visual conditions, its greatest potential contribution would be at night and in poor visibility. Greater effectiveness in these environments will promote increased operations under night and poor-visibility conditions.

Whereas under visual mutual support doctrine optimal defensive coverage dictates near-line-abreast element formations well within visual range, electronic mutual support favors formation arrangements better suited to the FOR of the electronic sensors involved. In the foreseeable future, the FOR for long-range offensive sensors is likely to be limited to the forward hemisphere of fighter aircraft. In addition, these sensors, under the concept of electronic mutual support, will most likely be the most capable defensive sensors. Purely defensive sensors, such as radar warning receivers (RWR) and missile warning systems (MWS), may extend defensive coverage to all aspects within a limited range. It is unlikely, however, that many tactics will be developed that place total reliance on purely defensive electronic sensors; but, more likely, these systems will be considered only supplementary to primary offensive sensors and visual coverage. Therefore, the most effective sensor coverage of the region surrounding a wingman will require formations in which aircraft to be defended electronically are located in the forward hemisphere of the defending fighter. This requirement can obviously be relaxed when remote supporting sensor platforms can provide adequate coverage for the flight.

Also, since the reliable range of electronic sensors is normally greater than the pilots' vision, formation spacing can be increased considerably. There are, however, several limitations on formation spacing. The first limitation is the effective range of the datalink, which may be constrained by LO considerations. Directional limitations of the datalink, such as blanking, may also constrain the geometry of effective formations. A second limitation is the effective range of friendly weapons. As in the case of visual

mutual support, detecting a threat is only part of the problem; negating the threat is the ultimate goal. This requires that a defending fighter be positioned to bring effective weapons to bear quickly on any detected threat.

In an environment that will be covered by external supporting sensors, both air-to-air and air-to-ground fighters will likely employ formations to optimize visual mutual support, i.e., line abreast, 1-3 NM for two-ship elements, with additional elements also line-abreast (Wall) or in 2-3 NM trail (possibly offset slightly to one side and/or with an altitude split of several thousand feet). These are essentially current tactics. The difference is that the fighters will likely run with active sensors off, or in Low Probability of Intercept (LPI) modes to enhance "stealthiness," at least until late in the attack phase of an engagement.

When a flight of fighters is in an environment requiring it to provide for its own defense, tactics are more likely to be optimized for electronic sensor coverage. This is difficult to accomplish effectively with a two-ship element and forward-hemisphere sensors, since both fighters' sensors can cover the rear hemisphere of the other only in converging situations, and these are only momentary conditions. Two-ship elements, therefore, will likely continue to use conventional visual mutual support tactics. Optimal advantage of electronic mutual support will require that flights comprise greater than two aircraft. Four-ship flights, or larger multiples of two, are preferable, since such arrangements allow employment of either visual or electronic mutual support as the situation dictates. One likely tactic is to employ an offensive element and a defensive element, each composed of a two-ship. The offensive element would lead the flight, probably in a passive stealth mode, followed by the defensive element in extended trail. The trailing element, with limited rear-hemisphere protection, would likely employ visual mutual support formations while providing active sensor coverage for the lead flight.

Released from the strict constraints of visual mutual support, the lead element is free to optimize its tactics offensively. Horizontal and vertical spacing within this element are restrained only by the limits of sensor coverage of the trailing element. Optimal offensive tactics dictate relatively wide horizontal and vertical spacing, arranged roughly line-abreast, for the lead element.

Another promising alternative is to employ the lead element in extended trail, followed by the defensive element line abreast. In this way the trailing element continues to provide sensor coverage for the lead element and weapons coverage for the lead-element wingman, while the lead-element wingman provides weapons coverage for his lead. Either of the above formations could be extended to multiple elements (Train or Ladder), with the trailing element providing defensive sensor coverage.

Offensively, both the above formations are naturals for cooperative-launch tactics. Leading elements can remain passive and launch weapons while trailing elements provide necessary guidance. Following launch, offensive elements can flow to the rear of the

trailing elements, assuming the defensive role as the trailing elements press the attack. Alternatively, the leading element can deploy for a pincer attack on the targets, possibly transitioning to visual mutual support near the merge.

In general, the availability of advanced threat weapons will decrease the advisability of "going to the merge" in air-to-air engagements. This factor will increase further the advantage of trail formations and cooperative-launch tactics. A launching fighter can quickly retreat from the effective weapons envelope of the enemy while relying on trailing elements to provide weapons guidance services, kill assessment, and follow-up attacks on the target if necessary. Depending on LO effectiveness, another possible option, particularly under non-visual conditions, may be to "blow through" the merge at high aspect, optimizing LO to the merge, then extending away from the threat. Maximum flexibility in such tactics is facilitated by flights composed of multiple elements and arranged in extended Train or Ladder formations.

Air-to-ground tactics are likely to be affected similarly to those described above for the air-to-air environment, particularly when the fighters are operating in a "self-escort" mode. Therefore, except during the actual attack, air-to-air defense will often be a prime concern. One difference in the air-to-ground mentality is a tendency to optimize defense rather than offensive air-to-air potential, since placing weapons on target is the primary objective.

In an environment well covered by external sensor platforms, the future fighter pilot on an air-to-ground mission will probably prefer to optimize LO capabilities by operating in passive or LPI sensor modes. In the air-to-ground mission, however, less-than-optimum friendly sensor coverage will more likely be the rule. In this case, trailing elements (at least) will probably employ active sensors. Extended trail (Train) formations are still optimum for most air-to-ground scenarios, but individual elements are more likely to continue to rely on visual line-abreast or echelon formations under visual conditions.

It is probable that the air-to-ground weapons of the future will stress stand-off delivery and autonomous or semi-autonomous guidance capabilities, much like air-to-air weapons. Expense and availability, however, will dictate that older weapons will continue to play important, possibly even dominant, roles in extended air-to-ground operations. During the Gulf War, unguided free-fall (iron) bombs represented the major (but least publicized) type of ordnance employed, supplemented by smaller quantities of more effective, but more expensive, precision-guided ordnance like LGBs.

In the future, we can expect the availability of an important intermediate class of ordnance: IAMs, with accuracy enhanced by Global Positioning System (GPS) and/or inertial guidance packages. Although not as precise as LGBs, this type weapon should be substantially more accurate than conventional Low Drag General Purpose (LDGP) bombs, especially when released from maximum stand-off distances. In addition, such weapons are independent of target illumination requirements after release. Because of

these advantages this class of weapon will most probably play a significant role in air-to-ground operations. Cost and availability will, however, continue to promote the use of conventional LDGP bombs whenever practical.

Because of the many limitations of semiactive precision-guided ordnance like LGBs, including weather restrictions, target illumination requirements, and relatively low delivery stand-off range, these are likely to be reserved for targets for which they are ideal. Such targets would be those requiring extreme precision, defended by only guns (AAA) and/or short-range SAMs, under acceptable weather conditions. For targets requiring somewhat less precision and/or under adverse weather conditions, IAMs are likely to be the weapons of choice. LDGP bombs will continue to be adequate and cost effective for most large-area targets in favorable weather. For "worst-case" targets, that is, those requiring high precision and long stand-off range in adverse weather, the preference would be for a longer range, autonomous or semi-autonomous precision weapon similar to the Navy's AGM-84E Stand-off Land Attack Missile (SLAM).

Probable air-to-ground delivery tactics relevant to an LO environment have been outlined above. Other than these implications, the inclusion of air-to-air datalink in the scenario will likely have little impact, except to improve pilot SA and possibly facilitate the coordination of complex attacks. An example of the resulting improvement in capability would be the ability to provide real-time target position updates and the tactical flexibility so necessary for effective attacks on relocatable targets.

One possible tactic that might be facilitated by air-to-air data-link is the air-to-ground equivalent of the cooperative launch. With semi-active weapons like LGBs, some form of target illumination, generally by laser, is required until weapon impact. This requirement may be relaxed if the weapon incorporates a passive or active tracking sensor, as with Maverick, Harpoon, SLAM, etc., for terminal guidance. Even with semi-autonomous weapons, however, some form of terminal guidance update may still be required or desirable. With long-range millimeter wave (MMW) radar or electro-optic (EO)/IR sensors it may be possible for one aircraft to maintain line-of-sight to the target, out of range of target defenses, providing target designation or illumination services while other aircraft launch precision-guided munitions from long range and low altitude or from behind obstructions like hills or mountains. Although such techniques have been practiced for some time (as with "buddy lasing"), the availability of air-to-air datalink may facilitate employment of this technique more effectively or allow its use with new weapons. In particular this capability may prove valuable against relocatable targets.

2.5 (Inverse) Synthetic Aperture Radar Considerations

Synthetic Aperture Radar (SAR) can provide a fighter with superior long-range mapping and stationary target location and identification capability. Employment of this technique requires the SAR platform to have a tangential velocity relative to the target which may complicate LO aspect-control techniques. The availability of air-to-air datalink could provide the future fighter with the ability to share SAR imagery generated

by a stand-off platform while employing optimal LO techniques, both by passive sensor operation and aspect control.

Inverse Synthetic Aperture Radar (ISAR) is a technique optimized for long-range detection and identification of moving targets, and does not require the tangential platform velocity of the SAR technique. This capability would be valuable against such targets as vehicles, ships, and aircraft. Once detection and identification is accomplished using ISAR, standard air-to-air or air-to-ground tactics may be employed, so the tactical implications are not highly significant. This capability may, however, allow precision surface attack under weather conditions that would preclude the employment of EO/IR/laser weapons, provided a weapon is provided to take advantage of this unique sensor technique. ISAR may also provide a method of non-cooperative target recognition (NCTR) superior in range to most current techniques, and less dependent on target aspect. Such improved identification (ID) capability would be very beneficial in allowing full exploitation of medium- and long-range weapons like the Advanced Medium Range Air-to-Air Missile (AMRAAM).

2.6 Thrust Vectoring Considerations

Thrust vectoring capability may range from simple thrust reversing to pitch-control vectoring to multiple-axis control to vertical takeoff and landing (VTOL) capability. Thrust-reversing allows an aircraft to slow down more quickly, either airborne or on the ground. Although theoretically shorter landing surfaces should be required by aircraft with thrust-reversers, in practice, runway requirements are most often dictated by heavy-weight takeoff rather than landing operations. Tactical airborne thrust-reverser operation would likely be limited to last-ditch efforts to generate an overshoot against an opponent, or to prevent an offensive overshoot, in a close-in maneuvering fight. Since such techniques would probably leave the fighter very vulnerable to further attacks, its employment would likely be reserved for very limited situations, much as speed brakes are used today. For fighters with supercruise capability, thrust reversing has increased utility in permitting rapid deceleration from high Mach to improve F-pole maneuvers or to reach the sub-sonic maneuvering envelope more quickly.

Thrust vectoring limited to the pitch axis can significantly increase a fighter's pitch agility, particularly at low speeds when aerodynamic controls are less effective. Although high speed pitch performance could also be improved theoretically, in practice aircraft structural and pilot physiological (G and G onset tolerance) limitations are likely to restrict employment above corner velocity. Once again, supercruise aircraft may have increased utility for high-speed pitch vectoring as a supplement to aerodynamic controls, which tend to lose some of their effectiveness at high Mach.

The only historical record of actual air-to-air combat by thrust vector capable fighters is the limited Falklands experience with British Harriers. Although the Harrier system was designed for takeoff and landing operations and is not strictly a pitch-

vectoring control, its effects are somewhat similar. It provides the aircraft with roughly one additional G above the airframe's aerodynamic limit when the nozzles are fully deflected. This added G becomes significant to maneuverability at low airspeeds. Some thrust-reversal capability is also provided. Thrust vectoring into the aircraft's vertical plane, however, results in a loss of longitudinal thrust, so the Harrier pilot is effectively going to idle power (or below) during such a "viffing" maneuver, with an accompanying rapid loss of energy. Because of this factor, although viffing is widely employed in British air-combat training, there is no record of it ever being employed in air-to-air combat in the Falklands. Pilots were reluctant to employ this technique in actual combat because they seldom found themselves in the effective viffing speed regime and were unwilling to sacrifice the energy required when actual bullets were flying. It should be noted, however, that the Falklands provided only very limited air-to-air combat under unique conditions, and any "lessons" must be considered accordingly.

In general, tactical pitch-vectoring capability will see its greatest application in slow-speed maneuvering and "nose-pointing." Pitch vectoring can provide the capability to increase angle of attack (AOA) above maximum aerodynamic limits at low speeds. Controlling the aircraft for extended periods in this regime, commonly termed "supermaneuverability," may also require roll and yaw thrust vectoring to offset aerodynamic moments. Pitch pointing normally results in much less loss of effective longitudinal thrust than is the case with the Harrier's "four-poster" vectoring system, but the resulting high AOA still generates excess drag. Such capability is largely limited to the very slow-speed regime and, therefore, will likely see little combat employment, since in combat pilots tend to follow the maxim that "Speed is Life." Although this is a capability fighter pilots will love, and will use extensively in training, its value in combat may not justify the added expense, weight, and complexity. Fighters engaged in this type of slow-speed dogfighting are highly vulnerable to virtually all hostile air-to-air and surface-to-air ordnance. A further consideration is control of the thrust-vectoring fighter's IR signature. Rapid reductions in power to reduce IR signature may be inhibited if aircraft control is to be maintained in the supermaneuvering arena.

Because of these factors, the increased agility provided by thrust-vectoring capability will most likely be reserved for those fleeting opportunities when a little additional performance provides an immediate weapons solution or could make the critical difference in defeating an opponent's weapon. These situations are also those in which the most successful Harrier pilots employ viffing tactics, rather than relying on this capability as a steady diet. This discussion should not be taken to diminish the value of pitch vectoring under selected conditions; but designers must consider the frequency that such conditions will be met in combat and the tradeoffs that are involved.

The most common tactics developed and observed in simulator studies of fighters with full three-axis thrust vectoring capability involve rotating the aircraft vertically or horizontally at very slow airspeeds and high AOA. These maneuvers can be impressive in providing the ability to point a fighter's nose at an opponent quickly, but in many cases, the resulting high AOA would preclude a successful offensive missile shot, since

the AOA exceeds the weapon's launch limitations. This is a factor that should be addressed by the designers of weapons-launch displays if thrust vectoring is considered for a future fighter.

To be effective, these maneuvers generally require very high thrust-to-weight. Even so, the drag generated is typically so high that energy is lost. At slow speeds, this normally means a loss of altitude. In other words, regardless of where the fighter's nose is pointed, its velocity vector very quickly points downward. This fact can severely limit the pilot's ability to employ radical thrust-vector tactics at very low altitudes, the very regime in which high design thrust-to-weight can be realized. If employed, therefore, these tactics will most likely be confined largely to low-to-medium altitudes. This is because very low levels are limited by velocity vector control, and very high altitudes are limited by reduced thrust-to-weight. This factor also has implications for future ground-collision-avoidance systems and displays.

2.7 Laser Radar (LADAR) and Millimeter-Wave (MMW) Radar Implications

In this discussion, there will be a distinction between laser range finders (range-only LADAR) and "scanning LADAR," which is more analogous to conventional microwave radar systems. The scanning systems will be addressed first.

LADAR has the potential for higher resolution than microwave radar techniques, with the tradeoff of generally shorter range due to atmospheric attenuation. Water vapor is especially critical in the effective range of LADAR. Since most of the water vapor in the atmosphere is concentrated at lower altitudes (below about 15,000 ft), long-range LADAR would be most practical as a high altitude air-to-air sensor. The value of such a sensor would be greatest for imaging target identification since, in general, the accuracy and resolution of microwave radar should be adequate for target detection and guidance of the air-to-air weapons likely to be available in the foreseeable future. The primary advantage of LADAR in this application is angular resolution, which would be valuable in providing the ability to resolve closely spaced targets at long range. Because of the limitations and technical difficulties of LADAR, it is unlikely that such a sensor will replace microwave radar in the near future as the primary air-to-air sensor, but an imaging LADAR target identification system, working in conjunction with a radar, is a possibility. Such a system might have greater range than current non-cooperative techniques under clear, high-altitude conditions, but likely would be employed much the same. One advantage would be supplemental identification capability over a larger range of target aspects than the current non-cooperative systems, which are quite limited.

If such a system was installed, and if it had autonomous tracking ability independent of the radar, it might be valuable for the future fighter pilot in avoiding detection by conventional enemy RWR at closer ranges. Long-range detection and tracking might be conducted using the air-to-air radar, transferring to the LADAR within range of that sensor. Of course, the fielding of enemy laser detectors might reduce the effectiveness of this tactic. Another advantage might be the ability to avoid enemy air-to-

air anti-radiation missiles (ARMs). Because of the extremely limited "side lobes" inherent in a LADAR system, an effective laser-homing ARM is not likely to be developed in the near future. In an ARM environment, the fighter pilot could shut down his microwave radar and operate only passive and LADAR systems.

In the air-to-ground arena, LADAR has the potential for more accurate ground mapping than microwave radar. Employment of LADAR for this purpose is, however, generally restricted by lower range. Because of these limitations and other technical considerations, it is likely that millimeter-wave (MMW) radar (particularly with SAR/ISAR capability) will prove to be the sensor of choice for future high-resolution ground mapping and ground target identification applications. MMW radar should prove sufficiently accurate for these tasks. One special application for which LADAR might be superior would be detection of targets with one extremely small dimension, like wires. This could be critical for terrain-following/terrain avoidance (TF/TA) applications, but it is doubtful whether this advantage alone would justify a LADAR TF/TA system.

The most prevalent current use of LADAR is in the form of laser range finders (LRFs). Because of their narrower beam widths when compared to microwave systems, an LRF generally projects a smaller "footprint" on the ground. This can result in superior air-to-ground range measurements critical to the accurate delivery of unguided ballistic weapons. LRFs also provide very accurate air-to-air range measurements for gun employment. The enhanced azimuth resolution of a tracking LADAR system could supply the inputs necessary for a very deadly all-aspect gunsight, leading to improved air-to-air gun effectiveness.

In general, MMW radar has the potential for increased accuracy and resolution over current radars, making it a prime candidate for application to ground mapping, TF/TA, target identification, and battle damage assessment (BDA). For these purposes, MMW radar would normally be less capable than LADAR, but without as severe range limitations under adverse conditions. The possibility of incorporating a MMW radar capability into a multi-function radar system also offers the prospect of lower cost than adding a completely independent LADAR system. MMW radar represents something of a middle ground in capability (range, accuracy, resolution) between standard fighter radars and LADAR.

2.8 Infrared Search and Track (IRST) System Implications

Air-to-air IRSTs, like forward-looking infrared (FLIR) systems, have been around for many years. Probably the most successful U.S. application was the F-106 interceptor developed in the late 1950s. Since that time, IRSTs have been part of the initial sensor suites of a number of fighter designs, but have generally been removed from operational models because of poor performance of the available technology and improvements in radar systems. Therefore, there is little IRST experience within the operational fighter community. More recently, interest has been rekindled by the inclusion of very capable

IRST systems on Soviet fourth-generation fighters and the advantage of passive sensors in LO environments.

As a passive system, the IRST has obvious benefits when considering LO capabilities and tactics. Although under some conditions an IRST may exceed radar in detection range, this system should, in general, be considered primarily a medium- to short-range sensor. Optimum conditions for target detection include a very high, fast target in afterburner, viewed from below and to the rear with a clear sky background, at night or with the sun at the sensor's rear. as with any IR sensor, IRST performance is degraded by humidity, clouds, rain, etc. Because of the many natural IR sources in the environment, IRSTs have been plagued with "false alarm" problems.

One of the primary limitations of passive systems is the difficulty of target ranging. The most common current technique for ranging with an IRST is by means of an LRF, slaved to the IRST line-of-sight. This combination can provide very high range and azimuth resolution while avoiding detection by conventional RWR systems. Due to these characteristics, IRST/LRF systems are ideally suited to provide gunsight data. They are also good supplements to Doppler air-to-air radar systems, which are optimized for detecting forward-aspect targets. Slaved, cooperative radar/IRST/LRF systems can offer high-probability target detection and tracking over the full range of target aspects.

The inclusion of air-to-air datalink and IRST in the Multi-Role Fighter (MRF) offers the prospect of exploiting passive ranging techniques. This would involve triangulation of target position by comparing the IRST lines-of-sight from two or more sensor platforms, eliminating the requirement for an active (detectable) ranging device. Since the accuracy of such a ranging technique is sensitive to the geometry of the sensors and target, employment would favor fairly wide splits between fighters, both horizontally and vertically.

Whether two-ship fighter elements would choose to employ such a split depends on many factors, most of which have been addressed above in the discussion of air-to-air datalink implications. Ideally, elements should be roughly line-abreast as widely separated as practical considering the situation, with a maximum practical altitude split, to optimize passive-ranging accuracy. Since such an arrangement does not enhance rear-hemisphere defensive electronic mutual support, additional more closely spaced elements might be employed in trail of the leading offensive elements in an environment not well covered by external supporting sensors. This leads naturally to the offensive-defensive division of responsibilities in tactics discussed previously to optimize LO and air-to-air datalink capabilities. Widely split offensive elements would lead the formation, employing passive LO techniques terminating in a "pincer or bracket" attack, while more closely spaced defensive element(s) are arranged in extended trail, operating under a combination of electronic and visual mutual support as appropriate.

The inclusion of IRST and passive ranging to the scenario provides the possibility that the leading fighters might be able to provide mid-course guidance updates to their

own AMRAAMs without relying on the cooperative-launch technique described earlier. This could improve LO capability when cooperative platforms are not available for such guidance, and could also allow supporting fighters to improve their own LO posture.

2.9 Miscellaneous Considerations

In addition to the above, there are a number of technologies which may be applied to a fighter in the near, to intermediate future. Many of these technologies do not represent revolutionary leaps in fighter capability, but rather enhancements to existing capabilities. Such technologies include flat panel displays, GPS, and digital terrain maps. In general, these technologies will not result in significant modifications to existing tactics, but rather will make these tactics more effective.

Better displays obviously allow the pilot to assimilate more information faster, improving SA. GPS allows more precise navigation, reducing the pilot's workload and facilitating target acquisition. High confidence in the performance and availability of GPS could also eliminate the need for visual or radar-significant targets, initial points (IPs), and low-level navigation turnpoints, thereby adding flexibility in surface attack planning and unpredictability in attack geometry. Also, as discussed above, GPS provides more accurate weapons targeting and makes practical a new class of weapon (IAMs) with near-precision accuracy at increased stand-off ranges.

The availability of precise navigation systems and digital terrain maps could provide the ability to project three-dimensional virtual images of the world outside the cockpit on head-down displays (HDDs), HUDs, and/or HMDs. Potentially, such a system could provide the pilot with an ability to fly "visually" at low level at night or in adverse weather conditions, much as though he were in a good visual simulator of today. Such a capability would greatly enhance the “stealthiness” of a future fighter, since active sensors would be unnecessary for TF/TA flight.

"Sensor management" is another technology with valuable implications in the near future. With the multitude of different sensors potentially available to new fighters, and the added workload burden on the pilot to control his electromagnetic signature for LO considerations, some sensor-management assistance will probably be required for optimal employment. The addition of air-to-air datalink to the scenario also opens up the possibility of intra-flight (or even inter-flight) sensor management for even greater potential benefits. Tasks for such a system might be to ensure complete coverage of the environment in all directions and at all altitudes of interest (sensor volume control), scheduling track file updates, providing weapon guidance updates, target ID, and signature control. It might even be possible to coordinate cyclic operation of the active sensors of various cooperating aircraft to confuse or defeat enemy detection while still providing complete, continuous sensor coverage for the flight.

An extension of this concept is often termed "integrated attack management." In addition to sensor management, an integrated attack management system might provide

for track correlation among the many sensors of the aircraft involved, assign threat priorities to targets, and calculate and display surface and air threat envelopes. It might even make suggestions to the pilot on "optimal" attack tactics.

A defensive corollary to integrated attack management is a defensive assets manager. Such a system might monitor and coordinate the various defensive sensors, such as the RWR and missile warning system, automatically deploy expendable countermeasures (chaff, flares, decoys, etc.), and operate jammers. It could also advise the pilot of optimal defensive maneuvers in response to detected threats, or possibly even take control of the aircraft if the pilot consents.

Essentially all the systems mentioned in this section would serve to make the fighter pilot more effective by reducing workload and/or improving SA. Such enhanced capabilities typically do not result in wholesale tactics changes, but may promote one tactic over another. For instance, as mentioned earlier, improved SA and defensive confidence tend to promote the offensive over the defensive, leading to wider formation spacing and more autonomy among individual fighters and fighter elements.

2.10 Multi-Sensory Virtually-augmented Display and Control Technology

2.10.1 Helmet-Mounted Display (HMD) Considerations.

HMDs can provide a fighter pilot with the capability to point weapons and sensors quickly at short-range visual targets in either an air-to-air or air-to-ground environment. The use of HMDs in air-to-air combat has been studied (Arbak, King, Jauer, & Adam, 1988; Olson, Arbak, & Jauer, 1991). Flight and weapons parameters can also be provided on an HMD, as is now commonly practiced on a HUD, so that the pilot can remain head-out for longer periods of time in the combat arena while maintaining SA.

Although such a capability should make the pilot more effective in combat, it should not have a great impact on tactics in the visual arena. The ability to display IR imagery on the HMD, however, can have more significant implications. In the air-to-ground mission, a Low Altitude Navigation and Targeting InfraRed for Night (LANTIRN) navigation sensor slaved to the pilots head position could greatly improve nighttime low-altitude SA as well as make visual formations as practical as in daylight. This capability would also allow offset pop-up attacks, which are standard in daylight, rather than the specialized straight-ahead pops normally employed at night with standard LANTIRN systems, adding flexibility and reducing predictability of the strike fighter.

Likewise, the HMD would be a valuable addition to an Automatic Targeting Hand-off System (ATHS) used to designate ground targets, particularly in Close Air Support (CAS) missions. Current systems normally use the HUD for target designation display, forcing the fighter to point very close to the target before designation can be displayed. This can result in the fighter inadvertently penetrating the target's weapons envelope and, at the very least, high closure with the target and late target designation

often make first-pass weapons employment difficult. With target designation displayed on the HMD, the pilot can "arc" the target area, remaining at a safe distance until the target is located, then set up for an effective attack from an optimal direction. During the actual attack, the target can be located much earlier, before the nose comes to bear, providing the pilot more time for effective weapons delivery.

In the air-to-air arena, in addition to facilitating visual formations at night, IR imagery provided on an HMD can make nighttime air combat maneuvering feasible, virtually "turning night into day." Maneuvering tactics may be constrained somewhat, however, by FOR limitations of the IR sensor. It is likely, for instance, that the IR sensor FOR may be restricted in its ability to look above or to the rear of the aircraft. In addition, the pilot's normal peripheral vision cues to the outside world will be limited, promoting disorientation and adding to the danger of ground collision. Because of these reasons, maneuvering is unlikely to be as unrestricted as in daylight. Additionally, because of the limited instantaneous field-of-view (FOV) of an IR sensor, maintaining multi-aircraft SA during a night maneuvering engagement will likely be difficult, increasing the probability of midair collisions. Therefore, fighters are likely to engage only one at a time in this environment, while the wingman "hawks the fight" maintaining visual contact, providing visual mutual support, and remaining ready to engage if the attacker loses contact with the target.

2.10.2 Three-Dimensional Audio.

Virtual auditory devices have been developed which utilize three-dimensional auditory localizers combined with audio image sources and stereo headsets. The three-dimensional auditory localizer samples the auditory image created by audio image source such as an intercom or computer-generated tone source, digitally filters the signal based on a head-related transfer function that is a function of sound location in azimuth, elevation, and range, and results in a stereo audio pair. The stereo pair is converted to an analog form and displayed over a stereo headset.

The potential utility of this technology for future cockpit interface design may lie in its ability to provide spatial auditory cues to pilots that can be interpreted more quickly and accurately than current display technology permits. For instance, localized auditory information specifying the origin of a radar warning receiver (RWR) tone may provide an advantage by providing an easily interpreted signal specifying the location of an enemy aircraft. The experiment discussed in Section 5 of this report evaluated the utility of this particular implementation of a three-dimensional auditory cue in an air combat setting.

2.10.3 Virtual Haptic Devices and Virtual Control.

Haptic displays, which enable the portrayal of virtual cutaneous and kinesthetic information, and other virtual control methods, are less developed technologies then the visual and auditory technologies, but may be made available for use as currently ongoing research advances. These include tactile/haptic stimulation devices, hand and body flexure measurement devices, direct vestibular stimulators, direct retinal displays, and

directly-coupled brain-actuated control. Control loaders, typically utilized in flight simulation to accurately model the stick feel of a particular aircraft, also fall into this category but are a mature technology. Virtual visual controls include helmet mounted head position/attitude trackers and eye line-of-sight trackers.

3.0 DEVELOPMENT OF VIRTUAL INTERFACES FOR FIGHTER AIRCRAFT COCKPITS

As previously noted, one of the major goals of the FITE Laboratory is to develop virtual interfaces for use in the cockpits of future fighter aircraft. As part of this effort we will conduct human factors research relevant to the design and use of virtual environments and virtually-augmented interface systems with primary relevance to cockpit applications, but with secondary relevance to other applications of virtual environments.

The determination of human factors research issues will be driven by two key factors: (1) the discovery of human performance problems during the use of laboratory prototype virtual environment systems, and (2) the anticipation of general research issues critical to the development of prototypes. In other words, the research program will be designed to respond to human performance data requirements raised during the prototype fabrication process, and it will simultaneously anticipate general classes of data requirements by pursuing critical avenues of research.

The rationale for employing a research strategy in which the iterative development of a prototype human-machine system becomes the central focus of the work is presented in detail below. However, it is important to note that all research conducted as part of this effort will be directly related to the ongoing development of prototype virtual environments for tactical cockpits. In some cases, research issues may be very specific to individual problems that arise with the development of a particular system. In these cases, there may be comparatively little generalizability of results to other virtual environment applications. In other cases, research will be conducted to anticipate general design requirements and to develop models of human performance in virtual environments. In the latter case, these results should generalize to other non-aviation and/or non-military applications of virtual environment technology.

While the generation of a database of human factors design guidelines in the form of empirical data will be a key emphasis, there are two other aspects of the research program that will be equally beneficial. One of these is the development of experimental paradigms that can handle the complexities of studying realistic human behaviors in relatively lifelike situations. The other will be the attempt to develop generalizable models of human performance in virtual environments.

At least two different varieties of virtual interfaces can be investigated in the FITE Laboratory: (1) fully-immersed virtual environments, and (2) virtually-augmented interfaces. Fully immersed virtual environments are defined as interfaces in which nearly all of the perceptual information available to a user is virtual in nature. Direct contact with the perceptual world may still be obtainable through the haptic and vestibular systems, as well as the senses of taste and smell. However, the "high information" senses

of vision and audition are exclusively driven by virtual displays in the case of full immersion. A virtually-augmented interface is any set of displays and controls that makes use of virtual technology, but which does not involve complete immersion of the user in a virtual environment. For instance, a virtually-augmented interface may only consist of a partial rendering of a virtual environment within the context of a real cockpit environment.

Our focus, as exemplified in the experiment described in this report, will be on facilitating the design of functional interfaces to be implemented in fighter aircraft cockpits. The overall goal of the program will be to provide design guidelines for cockpit virtual displays that will enhance pilot performance in tactical environments to the highest degree possible.

While our principal emphasis on the design of tactical interfaces for fighter cockpits is rather specialized, we anticipate the results of our research will have wide general application. Virtual environments are comparatively new technical phenomena, and much remains to be discovered about the human performance principles underlying their use. The elucidation of these principles will provide a very useful source of empirically-based information for the design and implementation of many types of virtual environments. We expect our work will generalize to many areas of virtual environment research and development in academia, industry and elsewhere in the private sector.

3.1 Prototyping as a Research Methodology

A major emphasis of the FITE Laboratory will be to continuously develop prototype virtual environment systems while simultaneously pursuing related human factors research. This approach serves at least two major functions:

(1) The ongoing development of prototypes permits an iterative approach to be taken with respect to the design of the final technical products, and

(2) The development of prototype systems will help illuminate deficiencies in our human factors database, thereby identifying useful avenues of research.

Development of prototype systems will be initiated at the earliest stages of the research and development effort. Human factors personnel within the laboratory will participate in this phase of the program by providing relevant human performance data. However, it is anticipated that ongoing prototype development will raise design issues for which no relevant empirical guidance exists. In this case, human factors personnel will design appropriate studies to obtain the necessary information. Therefore, deficiencies and problem areas identified during prototype development will serve as a major source of human factors research issues.

For example, engineering development and informal evaluations of prototype cockpit interfaces might lead to questions that require quick answers to make rapid design re-evaluation decisions. An example of such a question might be: "What is the minimum visual angle at which pilots can recognize a geometric pattern on a cockpit panel display as a threat?" Human performance data of this type will provide guidance on whether proposed interface equipment and configurations are sufficient in terms of meeting mission requirements. On the other hand, other issues can be anticipated to be important to the design of virtual interfaces, and research in these areas can proceed somewhat more independently of prototype design and evaluation. For instance, it can be safely assumed that in a fully-immersed virtual display pilots will need some sort of perceptual information to support the veridical perception of orientation. Since little is known about how to accomplish this, the best time to begin to investigate the issue is very early in the design process.

The major advantage of keeping the human factors research program closely tied to the prototype development process is that it increases the probability that findings will be directly relevant to the design of the technical system. In addition, the introduction of the emerging technical systems used in virtual environment will serve as a rich source of material for a broad range of human factors engineering research. This work should be geared toward generalized application toward virtual environments as a whole, insofar as that is feasible.

4.0 THE POTENTIAL UTILITY OF VIRTUAL ENVIRONMENTS IN FIGHTER COCKPITS

4.1 Tactical Cockpit Environments

Modern fighter aircraft present pilots with a number of significant behavioral and physiological challenges. Among these are difficulties related to high demands on perceptual and cognitive processes and physiological demands related to the unusual and occasionally extreme force environments characteristic of high-performance flight.

Specifically, problems arise with respect to at least three aspects of human performance: (1) workload, (2) situation awareness, and (3) spatial disorientation. Each of these areas present performance problems that can potentially be addressed by the implementation of virtual environments in the cockpit.

4.1.1 Workload.

The term "workload" refers to the general level of effort being expended at any given point in time by an operator interacting with a human-machine system. It can refer to the level of activity involved in information extraction processes (perception), information processing activities (cognition, problem-solving, decision-making, etc.), and system control activities (response selection and execution).

There are many factors that could potentially influence the level of subjective workload. Among those that are likely to be present in tactical aviation settings are: (1) the nature of the current tactical situation (e.g., routine patrol versus combat), (2) the number and complexity of factors that require the attention of the pilot (e.g., number and type of weapon systems and aircraft sub-systems), and (3) the state of fitness of the pilot and the current ability to process relevant information.

One of the major goals of designing virtual environments for tactical environments should be to reduce the overall level of pilot workload. This is especially critical in those situations (e.g., air-to-air combat) where the cost associated with errors of commission (executing an erroneous maneuver or other activity) or omission (failing to detect a critical piece of information) are extremely high. Measures of workload range from subjective to objective and can be employed in performance evaluations of virtual environments as a key measure of their effectiveness.

4.1.2 Situation Awareness.

The term "situation awareness" refers to a user's degree of cognizance of the status of external factors relevant to the operation of a human-machine system. In tactical aviation settings this refers to a pilot's awareness of such factors as the number and type of other

aircraft within the vicinity, number and type of ground-based threats, status of aircraft systems, status of weapons systems, etc.

The increased capabilities of modern fighter aircraft can result in increased demands on pilot situational awareness, particularly in combat situations. Errors of commission and omission are both likely to occur if pilots are insufficiently aware of the various environmental and tactical factors that influence their status in a given scenario.

Virtual interfaces may provide a useful technology for enhancing pilot situation awareness in situations where it is likely to be degraded. By taking advantage of the capability to present perceptual information to multiple sensory modalities, it may be possible to enhance both the quality and quantity of the information presented. However, there are significant design issues to be resolved in order to accomplish this goal. How to optimally combine multi-sensory information and how to exploit over-learned visual (iconic), auditory (earconic), and haptic information are two major areas of concern.

4.1.3 Spatial Disorientation.

Problems with spatial disorientation in flight have been well documented in recent years (e.g., Gillingham & Wolfe, 1986). In general, spatial disorientation is the manifestation of a partial or complete loss of sensory awareness of veridical orientation in three-dimensional space. The consequences of spatial disorientation are occasionally fatal in nature. In addition, the unusual force environments to which pilots of tactical aircraft may be exposed makes them particularly susceptible.

It may be possible to design virtual interfaces that enhance the perception of spatial orientation. For example, virtual displays could be designed to provide veridical representations of a pilot's orientation relative to the earth to guard against disorientation incidents while flying in clouds or fog. Virtual displays could also be designed which provide augmented perceptual information - that is, graphic information not directly representative of the real environment but which provides a schematic representation of the pilot's relation to the environment. For example, displays consisting of augmented artificial horizons could be devised that will enhance perception of orientation.

In fully enclosed virtual displays it will obviously be necessary to pay a great deal of attention to pilot orientation. In this case, research will need to identify the most salient types of perceptual information with which to communicate orientational information, as well as the most effective means of presenting it.

4.2 The Utility of Virtual Environments for Tactical Cockpits

As noted above, tactical aviation environments are characterized by occasionally extreme demands on pilots' perceptual, cognitive, and physiological capabilities. Increased aircraft performance capabilities and increased information extraction and processing demands will continue to create performance challenges for future generations

of pilots. One design approach to attempt to facilitate and enhance human performance in this type of environment is the development and implementation virtual interfaces for the cockpit.

Carefully designed virtual interfaces can offer a number of potentially significant advantages for pilots in tactical situations. Perhaps the most significant of these is ease of information extraction. One of the key themes underlying the development of these interfaces is the idea of optimizing the intuitive nature of perceptual information presented to the pilot. That is, properly designed virtual interfaces should present information in a manner that requires minimal demands on abstract reasoning and/or problem solving types of cognitive processes. Therefore, information about the status of weapons systems, aircraft sub-systems, threats, and other characteristics of the tactical environment should be conveyed in a way that minimizes demands on pilots' cognitive processes. However, the best technical approach toward achieving this goal will require significant empirical research.

In general, our approach is to develop empirically-based test strategies to contribute information critical to the design of prototype virtual interfaces. The criteria for these tests will be measures of human performance which, depending on the nature of the test, will vary from "operationally relevant" measures of aviation performance to more basic measures of perceptual-motor response. For example, tests and evaluations related to specific issues in the design of the prototype cockpit interfaces will, in many cases, be conducted using measures of aircraft and human operator performance that relate directly to the output performance of the system. Other evaluations may be more general in nature, and the performance measures of interest in these cases will be less directly tied to the performance of a particular system. Instead, these measures will be broader indicants of human behavior that will have greater generality amongst many different types of virtual interfaces.

Our overall approach to the design of virtual interfaces for tactical cockpits will be guided by two fundamental questions:

(1) What is the perceptual information that pilots need to attain their performance goals in a tactical environment, and

(2) What are the most effective methods for making this information available?

The first question deals with issues related to identifying critical sources of perceptual information needed to support pilot performance. There are many potential aspects of pilot performance relevant to the successful performance of a tactical mission. Each of these aspects of performance is likely to rely on the extraction of key perceptual information either directly from the environment (e.g., distance from friend or foe) or from displays within the cockpit.

Furthermore, the information may be of various types. Some types of perceptual information may be directly obtained from viewing the environment outside the cockpit. Information for the perception of self motion and orientation, for instance, may be obtained from the pattern of optical flow, the tilt of the horizon, and other types of information (Gibson, 1958, 1979). Other types of information may be more symbolic in nature. For instance, information concerning the status of aircraft sub-systems and weapons systems as typically displayed on cockpit instrument panel displays may be presented in more readily apprehended ways using virtual interfaces.

In many cases, the type of perceptual information that is needed is already known. For instance, pilots almost always need to be aware of their altitude, and therefore it is critical to provide them with that information. In other cases, particularly in the case of information directly perceived from the environment outside the cockpit, the information that is used may not be known. For example, our knowledge of what pilots attend to when perceiving their self motion and/or orientation may be insufficient to permit the development of guidelines for interface design. If this is the case, it will be necessary to pursue relevant research to identify the critical sources of information.

The identification of critical sources of perceptual information for tactical piloting tasks can be pursued through basic research conducted in the FITE Laboratory. Alternatively, such research might be pursued in one of our associate laboratories if any are better suited to fulfilling a particular research need. Once the key perceptual information has been identified, researchers in the FITE Laboratory will develop interfaces to incorporate that information. Evaluations of interface concepts will then be conducted using simulated tactical scenarios with experienced current or former USAF pilots as subjects.

4.3 Performance Measures

In order to make valid empirical decisions concerning the design and implementation of virtual interfaces for tactical cockpits, it is necessary to conduct performance evaluations of these interfaces in settings that approximate the demands of operational use. One key area of concern is to develop valid simulated mission scenarios in which to perform these evaluations. Another area of concern deals with the identification of measures of performance (or "dependent variables") to be used in these evaluations. The identification of valid and reliable measures of performance is one of the most critical initial areas to be pursued in the FITE Laboratory.

As part of the process of developing advanced human-machine systems, researchers need to concern themselves with specifying the behavioral goals of the technology they are developing, as well as methods for assessing for whether or not those behavioral goals have been met. In other words, researchers must be concerned with at least two general types of questions:

(1) What are the specific targeted aspects of human behavior which a given technology seeks to enhance, and

(2) What are the methods by which those behaviors can be measured in a valid and reliable fashion?

In the case of basic research conducted as part of this program to identify fundamental perceptual requirements of pilots in tactical situations, the question of performance measures may be relatively undaunting. For example, target detection performance, tracking accuracy performance, and other measures of basic perceptual-motor behavior are already well understood. However, the issue of identifying dependent measures becomes more problematic when dealing with performance evaluations of interface concepts. In this case, the behaviors to be measured need to be similar to those performed in real flight if valid inferences concerning the utility of the interface concept are to be made.

It is particularly critical that performance measures of simulated tactical flight meet two major criteria:

(1) Validity - The aspect of performance being assessed should be a true index of the desired target behavior, and

(2) Reliability - The psychometric properties of the selected measure of performance should be such that they are relatively stable and constant from one experimental trial to the next, all other factors being constant.

Air combat is an extremely complex task comprising numerous elements and sub-tasks that must be accomplished to produce a successful conclusion. Although each combat mission is different, it is possible to generalize many of the required sub-tasks. Once these elements are identified, suitable measures may be developed to quantify and predict pilot, aircraft, and weapon system performance.

4.3.1 Air-to-Air Missions.

Air-to-air combat missions vary in type and mission objectives, but, in general, may be broken down into the following broad phases: target search, intercept, weapons employment, and egress. In addition, a defensive reaction phase may be inserted at any point. Throughout all these phases are tasks that must be accomplished more or less continuously. These include:

- Navigation
- Maintaining flight parameters (aircraft control)
- System status monitoring
- Coordination with other friendly forces
- Defensive surveillance.

The form and priority of these background tasks change with the characteristics and phase of the mission. For example, in a Defensive Counter-Air (DCA) mission, the Target Search Phase is often performed while in a Combat Air Patrol (CAP) holding pattern. The primary objective of the Target Search phase of this mission is to detect enemy aircraft entering a specified volume of airspace. Navigation may be accomplished with reference to surface features identifiable either visually or by an onboard electronic sensor. Alternatively or coincidentally, electronic navigation aids, such as Tactical Air Navigation (TACAN), Inertial Navigation System (INS), or GPS, may be employed. Aircraft control involves maintaining the desired speed, altitude, heading, attitude, etc. This function is normally performed manually by reference to the outside environment and onboard flight instruments. Systems that require monitoring include aircraft operational systems (i.e., engines, fuel, electrical, hydraulics, communications, navigation, environmental, etc.), weapons (i.e., number and type available, their operational status, which type is selected, employment readiness, etc.), sensors (i.e., operational status and mode, field of regard, search volume, limitations, etc.), and defensive systems (i.e., operational status and mode, employment readiness, etc.). Coordination with friendly forces might be as simple as maintaining sight of one's leader or wingmen, or could involve complex interactions by voice radio or datalink. Alternatively, this function might be accomplished by coordinated timing or positioning with other elements of the defense. One example of this would be avoiding airspace assigned to other defensive elements. Here, as is often the case with background tasks, the navigation and coordination functions overlap. Defensive surveillance might be accomplished in conjunction with offensive search, but may also require the monitoring of defensive electronic sensors, scanning the surrounding airspace visually, or monitoring inputs from remote sensors and platforms.

When developing performance measures for the CAP mission, the most obvious are those that directly measure mission success. In this case, such measures might include survival of the friendly target assigned to protect, number of enemy aircraft destroyed, number of friendly aircraft lost, kill ratio, etc. These measures, however, are so high level and influenced by so many factors that they may be of limited value in assessing the effectiveness of candidate cockpit and display designs.

A more useful approach is to break the mission into phases and sub-tasks within each phase, then develop performance measures relevant to each sub-task. The resulting measures of performance, when taken individually, may not be of overwhelming importance to mission success, but collectively will determine the measure of that success. In addition, such an approach offers specific guidance to the cockpit and display designers on how to improve the overall probability of mission success.

As an example, useful measures for the Target Search Phase might include the number (or percentage) of hostile targets detected, number/percentage of hostile targets correctly identified, range of detection/identification (ID), time and/or distance of target penetration into the assigned airspace before detection or ID, etc. Each of these measures of performance could be calculated for each aircraft and for the flight as a whole. Even

this level of analysis, however, is of limited use to the cockpit/display designer, so sub-tasks must also be considered.

In the area of Navigation, relevant measures of performance might include the percentage of time each aircraft is within a specified distance from the designated CAP point. Another might be the percentage of detected targets outside the assigned airspace that generate a "commit" decision, as well as the percentage of detected targets within the assigned airspace that do not result in a commit decision. Likewise, another measure might be the length of time following target detection or ID that is required to assess the target's location within the assigned airspace.

Examples of performance measures relevant to aircraft control include the average errors from assigned or desired airspeed and altitude, the number of excursions beyond established bounds on airspeed, altitude, and attitude (about each axis), the average time required to identify excursions in these parameters, and the time and/or actions required to correct anomalies, etc.

Likewise, performance in the system monitoring function could be measured by the time and/or actions required to notice and identify correctly excursions in system parameters beyond established norms. Another is the correct identification of various pre-established critical fuel states, and the time and/or actions required for that identification. Other measures are something of a combination of the monitoring and the control functions. Such measures would be airspeed and altitude selection to optimize certain system performance factors. Examples of this are airspeed selection to maximize time on station or defensive maneuvering capability. Others include altitude selection to optimize sensor performance and target detection probability. Measures relevant to weapons monitoring would include the number of deviations from specified procedures for weapon selection, mode, status, etc., and the time and/or actions required to identify correctly such deviations. Likewise, the monitoring of sensors can be measured by deviations from specified procedures related to operational status, modes, search volumes, etc., and the time and/or actions required to detect and correct such deviations. Other measures could include the percentage of the assigned airspace volume effectively searched during the phase, or the percentage of the optimal coverage attained. Further measures would be the time and/or actions required for the pilot to detect and ID correctly a hostile target once detected by a sensor, as well as the percentages of valid/false contacts or correct/incorrect Ids.

Defensive system monitoring performance can be assessed by many of the same measures as described for offensive sensors. In addition, performance measures for defensive system operation related to expendable or other countermeasures may include the percentage of correct decisions in the type and timing of countermeasure employment, and the time and/or actions required to employ countermeasures following the detection of a threat.

Coordination with friendly forces can be measured in a number of ways. For example, the number and duration of deviations of wingmen from specified formation positions can be recorded. Since it is also common for pilots to coordinate individual sensor volumes to maximize coverage within a flight, these sensor volumes can be monitored to determine deviations from specified procedures. In addition, as mentioned above in relation to the systems monitoring function, the average percentage of assigned airspace covered by the flight's sensors, or the percentage of the optimum coverage achieved, would also be relevant to the issue of coordination. Cooperation during the Target Search Phase may also be assessed by measuring the number of targets or IDs passed within the flight, and the speed and accuracy of the information passed. Coordination with external friendly forces could be assessed by such measures as deviations from prescribed timing, number of contacts or target IDs that are passed to, or received from external sources, the speed and accuracy with which these contacts/IDs are passed, the number of targets in other's areas of responsibility on which the flight commits, the speed with which engagement instructions are received from an external controller once issued, etc.

Performance in the area of defensive surveillance can be assessed by many measures analogous to those listed above for the offensive Target Search Phase. Some definition would have to be developed to distinguish a "threat" from a "hostile contact." One possible means of discrimination would be to require threats to enter a hostile weapons employment envelope before detection. Some relevant measures include the number (or percentage) of threats detected, number/percentage of threats correctly identified, and the range of threat detection/ID. Each of these measures of performance could be calculated for each aircraft and for the flight as a whole. One important factor in defensive surveillance is visual search. Performance in this area might be assessed by measuring the percentage of time each pilot, and/or the flight as a whole, spends looking behind their aircraft, or behind the aircraft of the wingmen. This is a very imprecise measure, however, because of the limitations of the "visual sensor." We do not always "see" what we look at because of such factors as focus, contrast, background, non-foveal acuity, target motion, etc. A better metric might be to isolate the parameters of visual threat detection events from those of other sensors. The effectiveness of defensive surveillance, however, normally depends on the effective employment of all available sensors in combination.

In analyzing performance metrics of the sort listed above, it must be recognized that it is possible to have near-perfect scores on the metrics for every sub-task and still fail in accomplishing the assigned mission. The inverse case is also possible. Such situations may arise when pilots make bad tactical decisions based on good information, or prescribed procedures or tactics are not effective in the given situation. Such situations, however, are most often due to pilot inexperience or poor training. Cockpit designers should strive to provide the pilot with the most timely, accurate information practical in an easily digested format. In the long run this will result in the greatest potential for success. In assessing the performance of given cockpit/display designs, however, it is important that every effort is made to ensure optimal tactics are employed

in realistic simulated tactical environments. Otherwise, the conclusions reached are likely to be misleading.

4.3.2 Air-to-Ground Missions.

As with air-to-air missions, air-to-ground combat missions may generally be broken down into broad phases: Ingress, approach, target acquisition, weapons employment, and egress. Likewise, as in the air-to-air example, a defensive reaction phase may be inserted at any point. In general, the background sub-task functions the same for both missions.

As explained above, performance measures for the air-to-ground mission may be developed at the global level, by mission phase, and by sub-task within each phase. This process might be visualized by constructing a pyramid of performance measures, with the global measures of mission success, such as kill ratio or targets destroyed, at the top. These are supported by measures of performance for each phase of the mission, which are likewise supported by performance measures for each of the background sub-tasks necessary during each phase. Analysis of such a hierarchy of performance measures holds the greatest potential of providing the cockpit/display designer with guidance relevant to the specific design and performance areas that offer the greatest leverage in improving the potential for mission success.

For example, a poor kill ratio tells the investigator that something bears improvement, but gives no indication of where to look for design improvements. Investigating the next supporting level of performance measures, however, may show that the lowest scores are found during the Target Search Phase, and further analysis might indicate that sensor search volume is the prime culprit. Now the cockpit/display designer, who is probably limited by the sensor capabilities available, might look at improving sensor volume displays or developing methods for improving coordination of search volumes among cooperating platforms. An iterative process based on this methodology offers the greatest promise of development efficiency.

The following section presents a discussion of an experiment that was performed to initiate just such an iterative approach. It represents the first effort of the SIRE Laboratory to evaluate the effect of novel cockpit interface concepts on the performance of a simulated air-to-air combat task.

5.0 PRELIMINARY EVALUATION OF A COCKPIT INCORPORATING MULTI-SENSORY DISPLAYS

5.1 Introduction

The purpose of the experimental evaluation described in this section was to initiate the program of research described in the preceding portions of this report. Specifically, our goal was to conduct an evaluation of a novel F-16 cockpit interface configuration (referred to below as the "Modified" interface condition) by contrasting performance on a simulated air-to-air combat task with a more conventional array of cockpit interfaces (referred to as the "Conventional" interface).

While our primary intent was to empirically assess differences in pilot performance and situation awareness as a function of the two different cockpit interface configurations, the current effort also involved the development of two critical components for future investigations: (1) a representative air combat scenario involving multiple actors operating in real time in the same virtual airspace, and (2) an on-line performance measurement capability.

5.2 Method

5.2.1 Subjects.

Four male fighter pilots from the United States Air Force served as subjects. Their ages ranged from 26 to 34 years with a mean of 31 years. Their relevant flight experience, which included F-16A/B, F-16C/D, MD-88, B-727, T-37, T-38, and F-4 aircraft, ranged from 1,190 to 4,000 hours with a mean of 2,322.5 hours. In addition, subjects reported having attended a variety of special fighter training courses including: USAF Fighter Weapons School, Red Flag, Green Flag , Cope Thunder, Team Spirit, and USAF Instructor Pilot Course. All subjects had normal or corrected-to-normal vision, and reported that they had not previously participated in a flight simulation experiment. Subjects were paid for their participation.

5.2.2 Experimental Design.

Two cockpit interface designs (Conventional and Modified, described in detail below) were combined factorially with three threat aircraft initial altitudes (low, medium, and high) to provide six experimental conditions. A within-subjects design was used in which each subject participated in all experimental conditions over a two day period. The order in which subjects received the experimental conditions is presented in Appendix A. Subjects' performance, as measured by various fighter performance criteria, and their level of situation awareness during the air-to-air combat missions served as dependent measures. A complete list of the fighter performance data collected during the experiment is contained in Appendix B. A copy of the Situation Awareness

questionnaire is contained in Appendix C. At the conclusion of the experiment, subjects evaluated the Conventional and Modified interface designs by completing a post-experimental debriefing questionnaire (Appendix D).

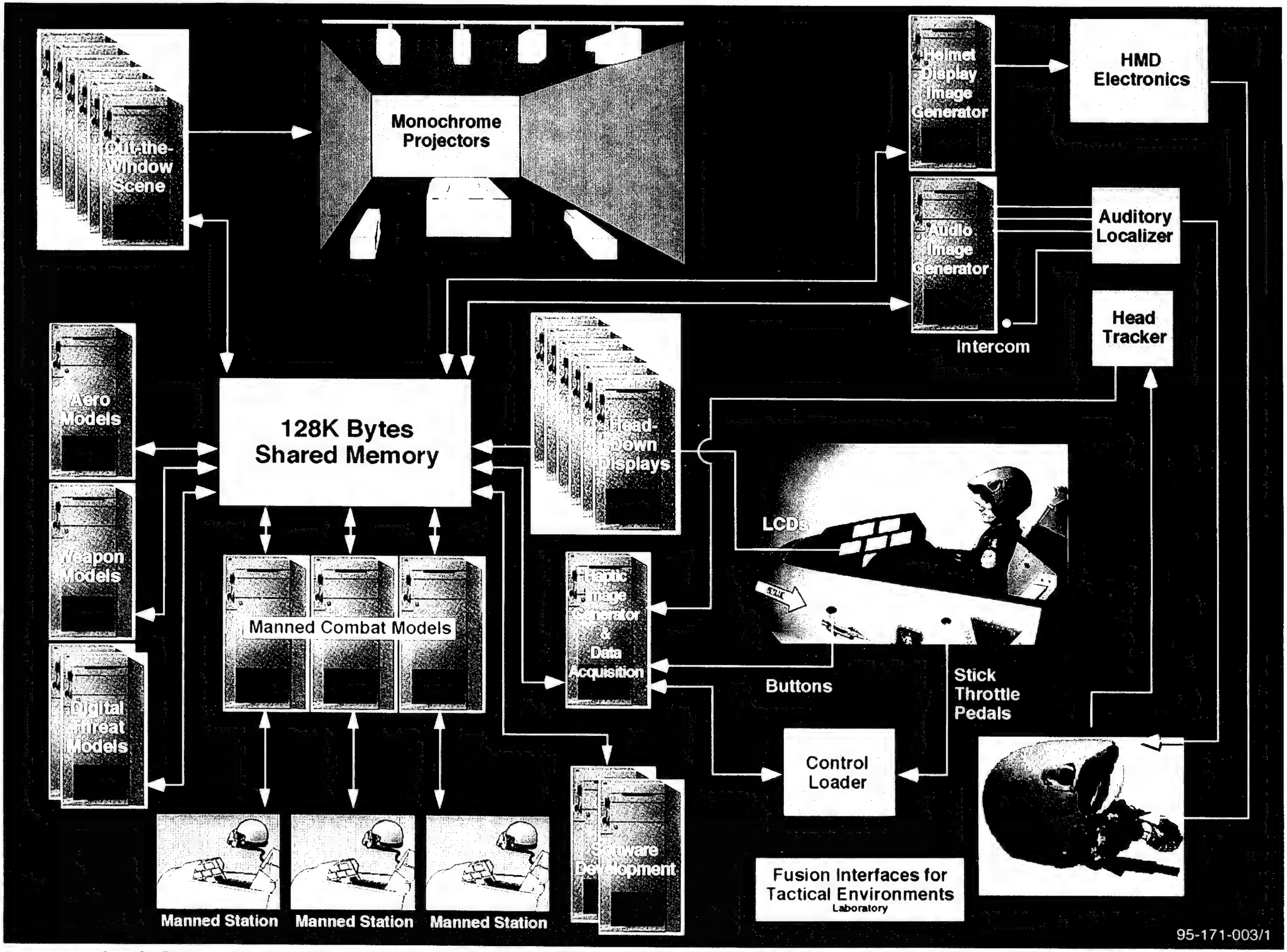
5.2.3 Apparatus and Procedure.

All subjects participated in several one (principal cockpit) versus two (enemy fighters) air-to-air combat scenarios in which the primary task of the principal cockpit was to eliminate four enemy bombers and then return to safe air space. The four bombers were protected by two enemy fighters whose primary task was to eliminate the principal cockpit. Throughout the experiment, subjects flew 12 trials as the pilot of the principal cockpit, and 24 trials as the pilot of an enemy fighter. All subjects flew six cockpit trials using a conventional F-15 interface, and six trials using a modified cockpit interface. The principal cockpit was accompanied by a pre-programmed, friendly F-15 fighter that flew a pre-determined route, but did not deploy weapons at either the bombers or the enemy fighters.

Cockpit and Displays. The experiment was conducted in the FITE facility. A block diagram of the FITE facility is presented in Color Plate 1. The cockpit used in the present experiment was a fixed-base simulator that consisted of an F-16 fiberglass body, head-down displays, an F-16C throttle, and a sidestick controller. The cockpit was housed in a cubic projection room that measured 8' x 8' x 8'. All visual, auditory, and haptic displays were controlled by a network of 23, 486 - 33 MHz microcomputers. The displays used in this experiment included an out-the-window display (OTW), several head-down displays (HDDs), a head-up display (HUD), a helmet-mounted display (HMD), and localized and non-localized auditory displays.

The out-the-window (OTW) display, which included buildings, clouds, ground patterns, and other aircraft, was projected onto the surface of the cubic projection room by six, black and white Limelight projectors, each of which was driven by a 486 - 33 MHz microcomputer. The OTW display was projected onto the left, right and front walls and the ceiling of the projection room. This arrangement provided subjects with a 240^{o} (horizontal) X 120^{o} (vertical) field of view (FOV). The horizontal FOV was +/- 120^{o} from the design eye, whereas the vertical FOV ranged from 30^{o} below to 90^{o} above the design eye . A schematic of the cockpit and the cubic projection room is illustrated in Figure 5.

The head-down displays, which were located on the front panel inside of the cockpit, consisted of six, rectangular, color liquid crystal displays (LCDs). All of the LCDs measured 9 cm X 12 cm, and had 1040 x 1280 pixel resolution. Each LCD was controlled by a 486 - 33 MHz microcomputer, and had an update rate of 30 Hz. The general configurations of the LCDs in the conventional and modified F-15 cockpits are presented in Figures 6 and 7, respectively.



Color Plate 1. Block Diagram of FITE Laboratory

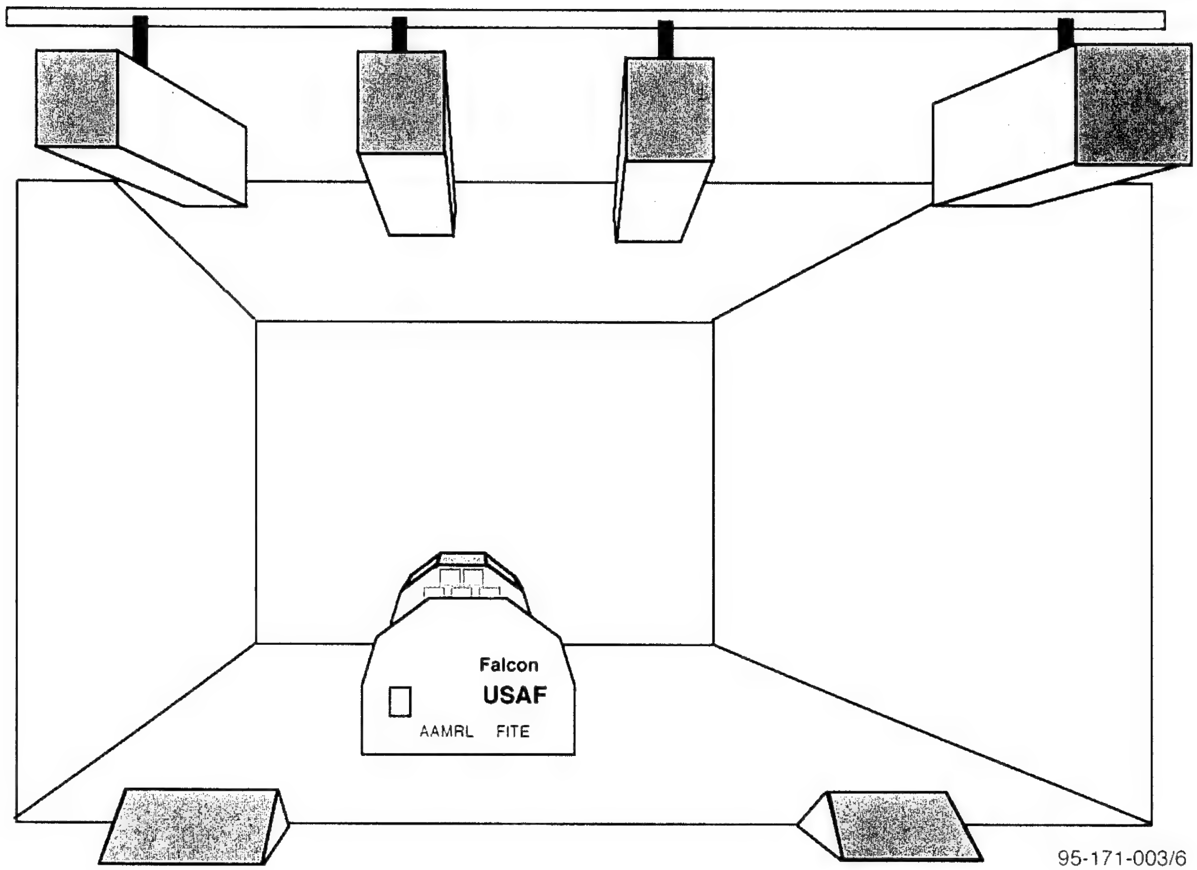
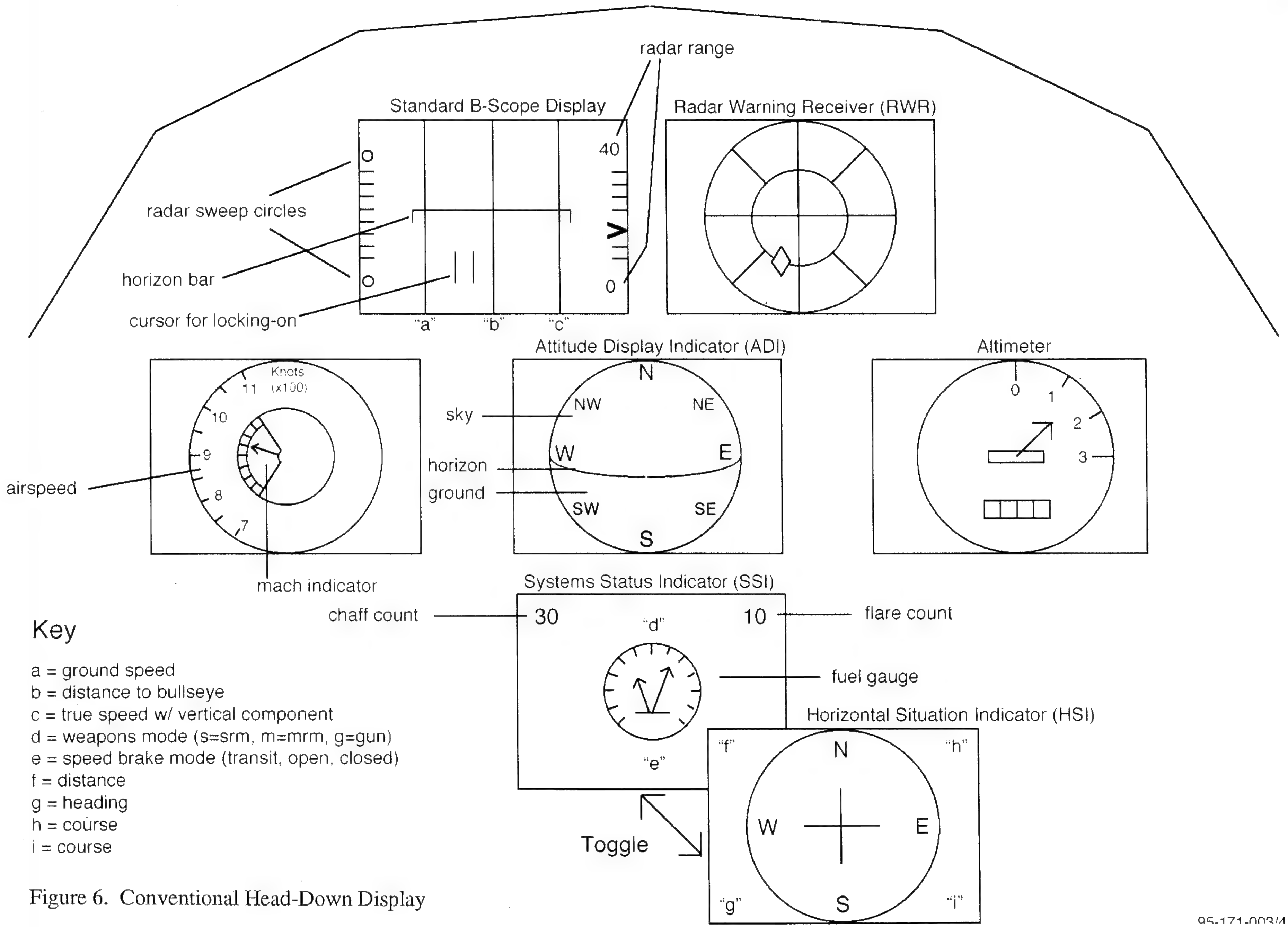


Figure 5. Schematic of the FITE Laboratory and Display Projection Surface



Key

a = ground speed
b = distance to bullseye
c = true speed w/ vertical component
d = weapons mode (s=srm, m=mrm, g=gun)
e = speed brake mode (transit, open, closed)
f = distance
g = heading
h = course
i = course

Figure 6. Conventional Head-Down Display

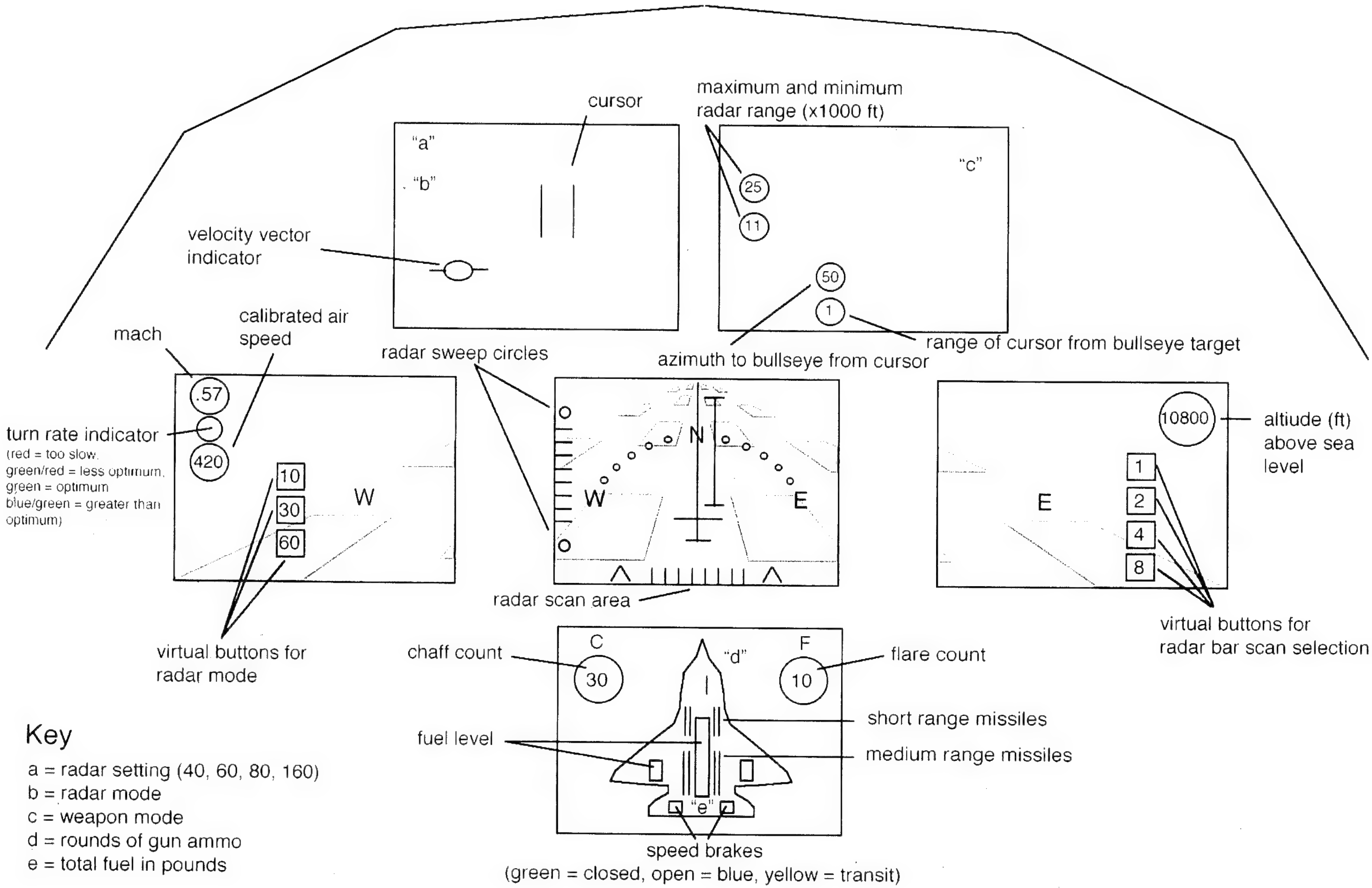


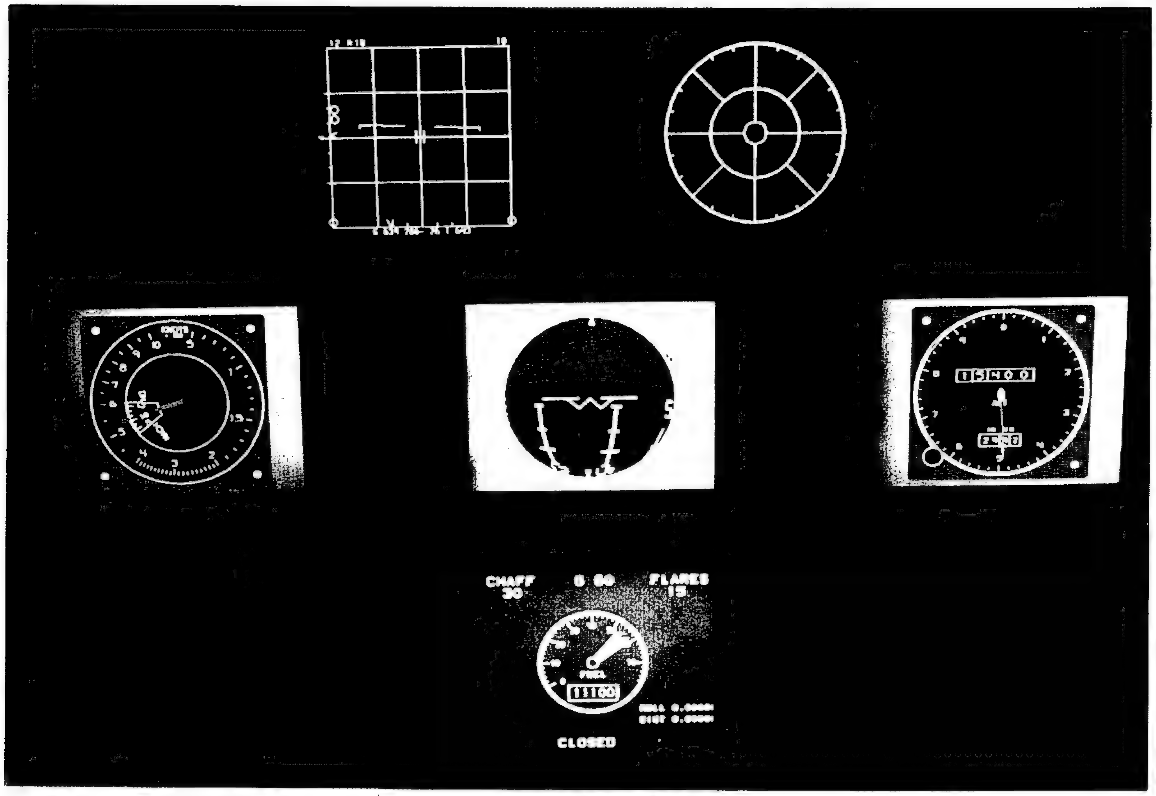
Figure 7. Modified Head-Down Display

As can be seen in Figure 6 (also Color Plate 2), the LCDs in the Conventional cockpit's HDD were used to present an array of standard cockpit displays that included (from left to right and top to bottom): an air-to-air B-scope display, a radar warning receiver (RWR) display, an airspeed indicator, an Attitude Display Indicator (ADI), an altimeter, and a dual-function display that consisted of a Systems Status Indicator (SSI) and a Horizontal Situation Indicator (HSI). In the case of the dual function LCD, pilots were able to manually toggle between the SSI and HSI displays.

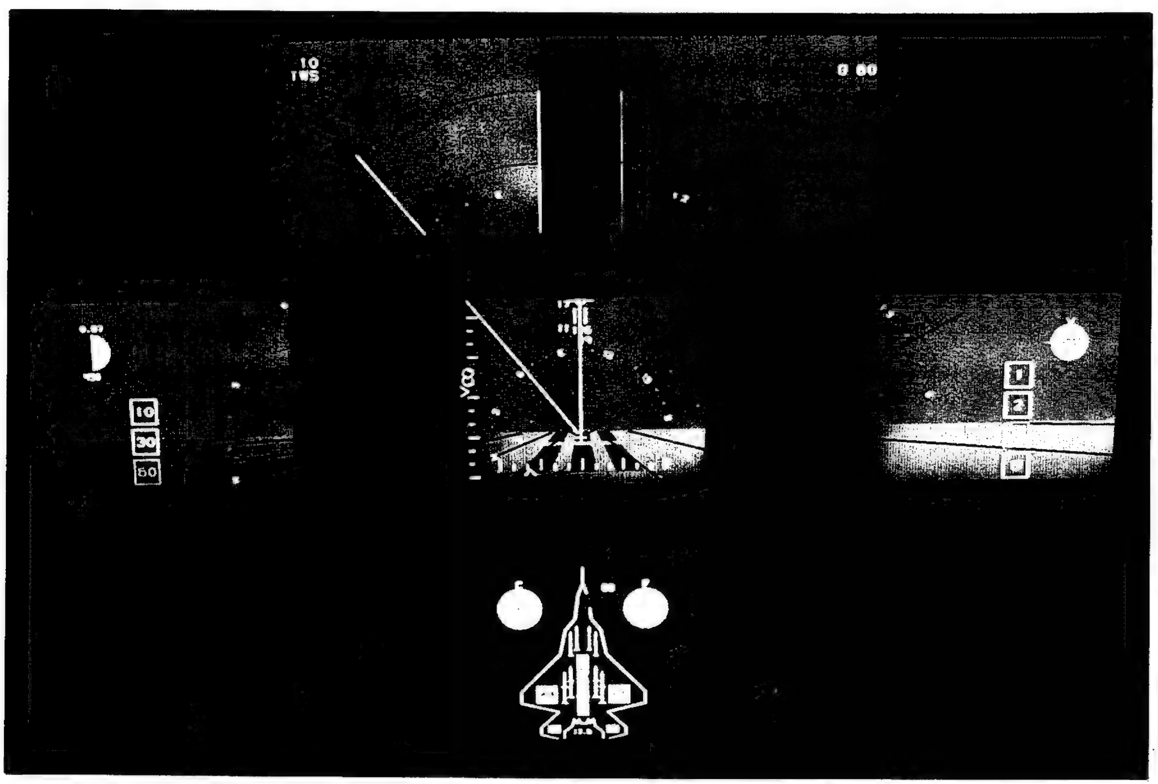
The B-Scope display, RWR display, airspeed indicator, altimeter, ADI, and HSI all employed instrument designs that closely replicated traditional fighter cockpit instrumentation. The SSI, however, was designed as a composite display in order to maximize the use of the HDD's limited display area. The SSI provided pilots with several sources of information that are considered relevant to air combat missions. As shown in Figure 6, the SSI consisted of a weapons mode and count indicator, chaff and flare count indicator, a fuel gauge, and a speed brake mode indicator. Although the SSI is not a standard fighter cockpit display, it employed traditional symbology to display its information.

The modified HDD, which is illustrated in Figure 7 (also Color Plate 3), consisted of a pseudo large-screen display - generated by coupling the upper two rows of LCDs - and a single LCD display located at the bottom of the HDD. The large screen display provided pilots with a simulated out-the-window display including a horizon line, ground (light tan), sky (light blue), and moving ground textures (brown blocks). The simulated OTW display also incorporated several powerful monocular depth cues. First, as can be seen in the figure, ground textures were drawn in linear perspective, indicating the distance from the aircraft to the horizon. Second, ground textures were presented in streaming perspective when the aircraft was in motion. That is, the ground textures appeared to move from the horizon line (far) toward the aircraft (near) at a rate that was proportional to the aircraft's ground speed. Third, the size of the ground texture was inversely related to the aircraft's altitude. Thus, increases in altitude caused the ground texture to appear smaller and more distant. Altitudes above 10,000 ft, however, were not accompanied by decreases in ground texture size. The single LCD located at the bottom of the modified HDD was the System Status Indicator (SSI) display, and it was used to provide pilots with mission relevant information including weapons mode and counts, chaff and flare counts, speed brake information, and fuel quantity information.

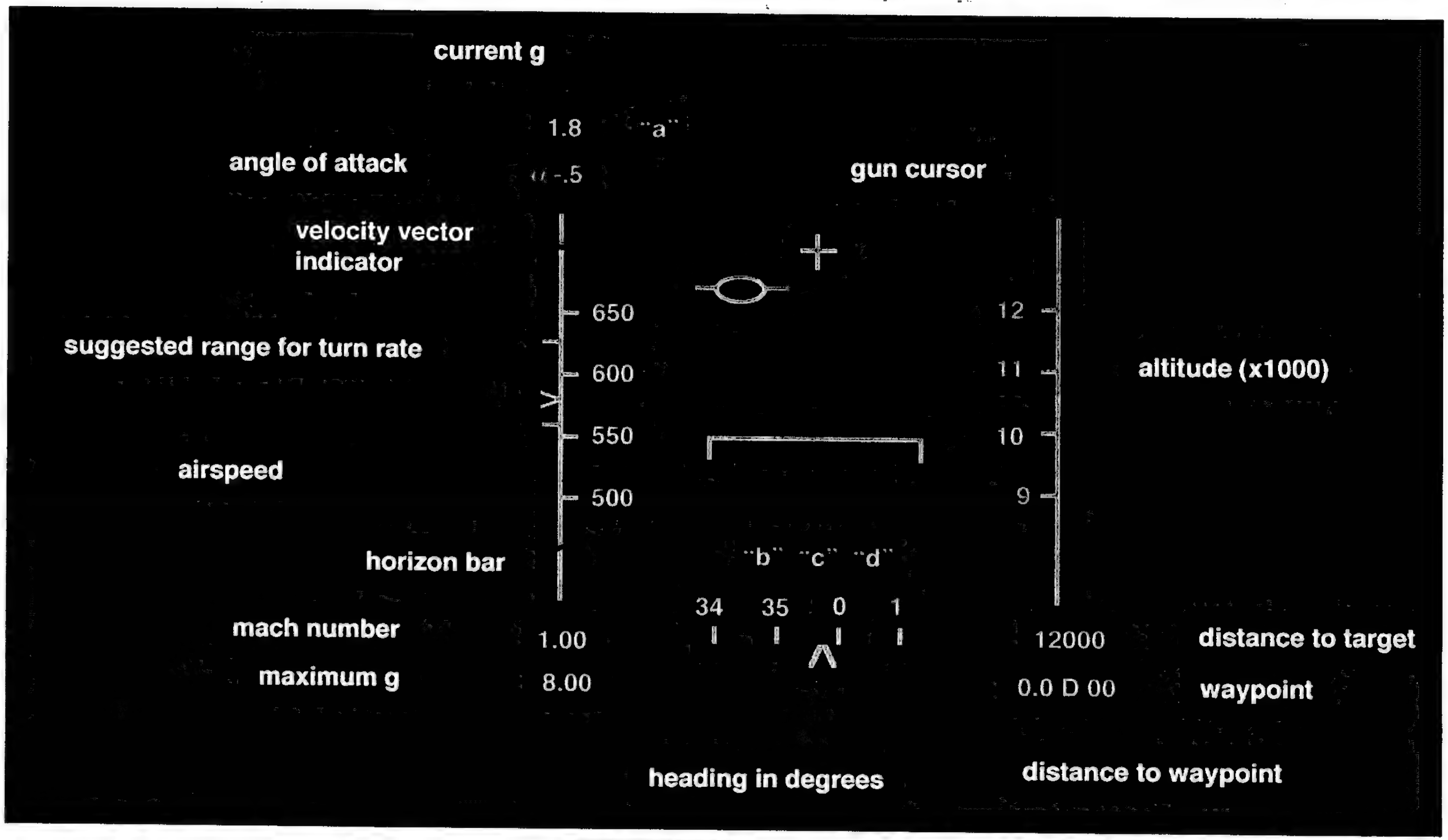
The head-up display (HUD), which is illustrated in Figure 8, was projected onto the center of the front projection screen, directly in front of the cockpit. The HUD was generated with a 486 - 33 MHz microcomputer in combination with a green monochrome Limelight projector. It was focused at infinity, and occupied a $20^{o} \times 20^{o}$ field of view. In both cockpit conditions, the HUD was used to provide pilots with information regarding the status of numerous flight parameters, as well as information regarding the navigation, radar, and weapons systems. The layout of the HUD used in this experiment closely approximated the "declutter mode" format employed in contemporary fighter HUDs.



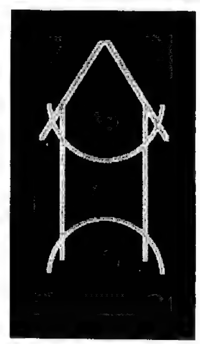
Color Plate 2. Conventional Head-Down Display



Color Plate 3. Modified Head-Down Display



Key
a = weapons mode (g=gun, srm=short range missile, mrm=medium range missile)
b = speed brake indicator
c = chaff count
d = flare count



Ground Collision Avoidance System (GCAS)

* GCAS is triggered by an impending ground collision. During a GCAS warning, a red GCAS symbol "pops-up" in the middle of the HUD, and in the HMD. The arrowhead always points to the sky. The closure rate of the semi-circles represents estimated time to ground collision.

Figure 8. Head-up Display

A Kaiser Electronics Agile Eye (monocular) helmet-mounted display (HMD) was used in the modified cockpit condition. The Agile Eye HMD was equipped with a transparent ("see through") visor that allowed an auxiliary HUD to be presented to the pilots whenever their line of sight was aimed away from either the HDD or the primary HUD. In other words, the HUD in the HMD would "pop-up" whenever the pilot was not looking straight ahead or down at the HDDs. The format of the HMD's HUD was almost identical to the main HUD, except that a "hot box" feature replaced the gun cross and several radar mode indicators. The "hot box," which appeared as a rectangle in the center of the HMD's HUD, was used to lock on targets by moving one's head so that the "hot box" captured the target.

Auditory Displays. All cockpit trials were accompanied by an array of meaningful sound effects that were presented to subjects via a set of headphones inside of the flight helmet. In addition, air and engine-noise sound effects were produced with a noise generator and were played over a set of external speakers positioned directly behind the cockpit. The presentation of the sound effects in the helmet was controlled by three 486 - 33 MHz microcomputers in conjunction with Sound Blaster Pro software. Each sound computer was assigned four different sound effects. However, each sound computer was restricted to producing only one sound effect at a time. Thus, it was necessary to prioritize the sound effects for each computer. Table 1 lists the sound effects - from highest to lowest priority - associated with each computer. If two sound effects were activated by one computer, the sound effect of highest priority was played over the headphones. No priority, however, was given to sound effects produced between computers.

Table 1
Prioritized Listing of Sound Effects Presented in the Cockpit

	COMPUTER	
I	II	III
Guns	gcas_1	RWR detection beeps
missile whoosh	gcas_2	missile RWR
missile growl_1	missile lock	fighter RWR
missile growl_2	joker fuel	bomber RWR

All of the sound effects produced by computer I were non-localized. In contrast, computers II and III produced sound effects that were localized to their respective sources. The Conventional cockpit only received sound effects that were produced by computer I (non-localized), whereas the modified cockpit received sound effects from all three computers. The localization of the sound effects was controlled by a Convolvotron, a hardware and software system that generates apparent three dimensional spatial sound for headphone presentation. The Convolvotron provides four channels of output

consisting of stereo audio signals, and also accommodates input in the form of direction angles and strength for each of the four output channels.

Weapons. Gun Models. The gun and gunsight models were identical in both interface conditions. The gun model simulated a simplified 20 mm Gatling gun, with an initial loadout of 600 rounds of ammunition and a firing rate of 6000 rounds/min. In the Conventional condition, gun mode selection was indicated by an alphanumeric display that appeared at the top of the SSI - a "G" followed by the number of rounds (x10) remaining. Similarly, all of the HUD displays indicated gun mode by displaying this alphanumeric information. In contrast, gun mode selection in the modified condition was confirmed by a color-coded symbol - a blue gun in the nose of the fighter aircraft icon - displayed in the SSI and was followed by a digital readout of the number of rounds remaining.

Missile Models. Both interface conditions were outfitted with four Medium Range Missiles (MRM) and four Short Range Missiles (SRM). The MRMs and SRMs were modeled as simple, radar-guided, air-to-air missiles, that generated flight profiles, and guidance characteristics and limitations representative of contemporary air-to-air missiles. In the Conventional interface condition, the selection of the MRM and SRM mode was indicated by an alphanumeric display that appeared at the top of the SSI. That is, when a missile was selected the letter "M" or "S" - MRM and SRM respectively - appeared in the top left corner of the SSI and was followed by a digital readout of the number of available missiles. Similar alphanumerics also appeared in the upper left corner of the HUD. In the Modified condition, pilots were able to verify their missile mode selection in two different ways. First, a color coded symbol that appeared in the SSI was used to indicate missile mode selection. More specifically, if the SRM mode was selected, a short range missile icon in the SSI turned blue, and after it was deployed it disappeared from the SSI. In addition, an alphanumeric digital readout of the selected missile mode and count appeared in the upper-left corner of the SSI.

Sensor Models. Radar. The Conventional and Modified interface conditions employed a simplified simulation of a modern pulse-Doppler (PD) air-to-air radar with Track-While-Scan (TWS), Single-Target Track (STT), and Close-In Combat (CIC) capabilities. The Conventional interface condition also included a Range-While-Search (RWS) mode. The CIC mode provided several options for establishing radar locks in short-range (within a 5 NM range), highly dynamic combat situations including Boresight (BST), Slewable Scan Lock (SSL), and Vertical Scan Lock (VSL). Additionally, the Modified condition included a HMD mode that permitted pilots to control the radar using their flight helmet.

The BST mode permitted pilots to quickly lock on a target by positioning a "hot box" display, which appeared in the center of the HUD, within $\pm 2^{o}$ of the target. The HMD mode in the Modified condition was analogous to the BST mode in the

Conventional condition except that the "hot box" was centered in the HMD's HUD. Thus, pilots in the Modified condition were able to lock on a target by aligning it with their line of sight.

The RWS mode, which was only available in the Conventional condition, provided search-only capability representative of the search modes of typical current air-to-air radar, with analog display of contact positions and altitudes. The RWS mode permitted early and accurate target detection. Radar contacts were displayed as small rectangular blocks, and round target-history "dots" were used to aid in visualizing target movement.

The TWS mode permitted pilots to maintain simultaneous "track files" on multiple targets. In addition, the TWS mode provided pilots with information on target speed, altitude, course, and, in conjunction with the Target Identification System (TID), information on the class and type of target. The TWS mode permitted pilots to select a range scale of 10, 20, 40, 80, or 160 NM, an azimuth of $\pm$ 10, $\pm$ 30, and $\pm$ 60, and rotate the radar antenna up or down 60 degrees from level. The TWS mode also included an elevation bar option of 1, 2, 4, or 8-bar scans.

The STT mode provided pilots with the greatest possible accuracy and information on a single target. Pilots were able to manually activate the STT mode from the RWS and TWS modes, or automatically from the CIC mode.

Radar Warning Receiver (RWR). Both interface conditions employed identical RWR models -- a highly simplified simulation, intended to represent typical performance capabilities and limitations of current operational RWR systems. The azimuth accuracy of the RWR model was $\pm$ 5^{o}, while range accuracy was approximately $\pm$ 20%. The RWR model differentiated between various radar types [i.e., threat fighter, friendly fighter, range-only, air-to-air missiles (AAM)], and operating modes (i.e., search or track).

The Conventional RWR system was displayed on the upper right LCD of the HDD and was completely automatic. Symbols representing air-to-air threats appeared on the display indicating the approximate azimuth and range of the detected radar emitter. Increases in the strength of the threat's radar signal caused the threat symbol to move closer to the center of the RWR display. New emitter symbols on the RWR display blinked at a rate of 5 Hz for the first 4-sec, and were accompanied by an auditory warning signal - eight, high-pitched, "beeps"- that were played over the pilot's headphones. Following the initial auditory warning signal, a tone that represented the pulse-repetition frequency (PRF) of the detected radar was played over headset.

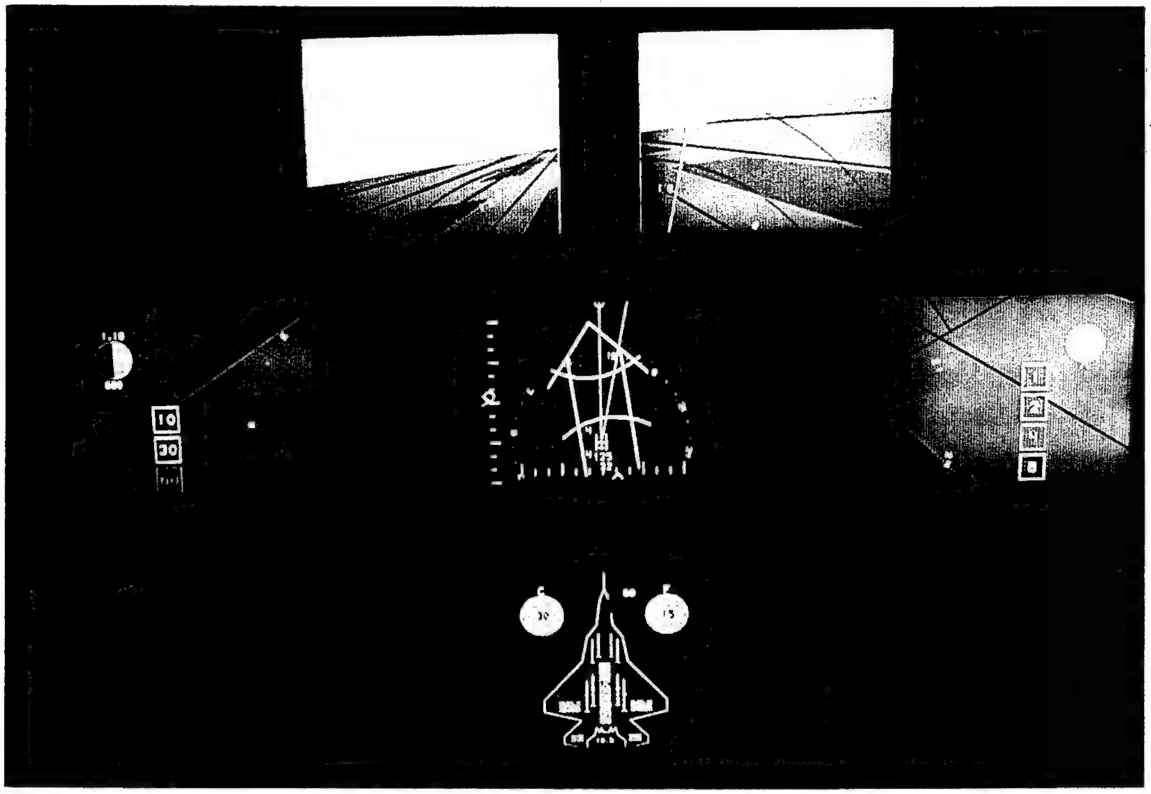
The Modified RWR system was also fully automatic, and did not have any associated controls. Detected emitters were indicated by colored "fans" that extended from Own Aircraft Symbol in the HDD along the azimuth of the emitter. Angular uncertainty and the estimated range of the detected signal was represented by the width and length of the "fans," respectively. The color of the "fan" denoted whether the emitter

was classified as threat (red) or friendly (blue). Emitter type was represented by the pattern, pulse radar "fans" were single-hashed, and active AAMs generated "polka-dotted" fans. The "fan's" blink rate specified the operating mode of the emitter. Search and TWS emitters were identified by a "fan" that blinked at the sweep rate of the antenna, while STT mode was denoted by a steady "fan."

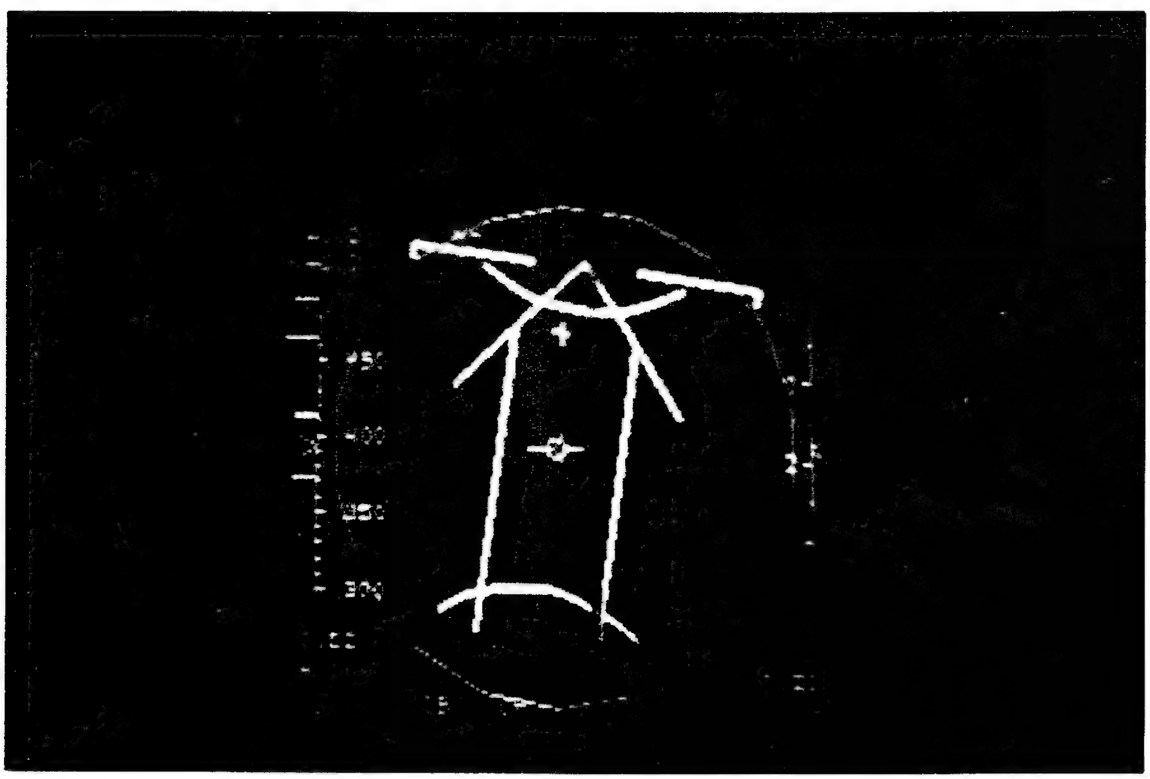
The Modified RWR system employed the same auditory warning signals as the Conventional system. however, warning tones in the Modified condition were localized with respect to the direction of the emitter. Additionally, the volume of the auditory tones varied inversely with the distance of the emitter.

Target Identification System (TID). The TID system model was a highly simplified simulation intended to represent the current capabilities of both cooperative (transponder-based) and non-cooperative (radar-signature-based) target identification and recognition systems. The capabilities of the TID system were identical in the Conventional and Modified conditions, and both systems were completely automatic. The TID system was operational in either TWS or STT radar modes. Assuming the target has an operating transponder, classification (i.e., friendly or hostile) can be expected within a few seconds of establishing a track file (TWS) or lock (STT) out to the limits of the radar's detection capability. Identification (i.e., type) typically takes somewhat longer and is dependent on the range and aspect of the target.

Ground Collision Avoidance System (GCAS). The Modified interface condition included a Ground Collision Avoidance System (GCAS), which served to warn pilots when immediate action was required to avoid collision with the ground. The GCAS utilized information about the aircraft's current height above the ground, descent rate, dive angle, airspeed, and bank angle to compute an alert altitude. Based on these calculations, a GCAS alert was issued to allow the pilot a minimum of 4-sec to begin recovery from a dangerous flight path. The GCAS alert was displayed on all visual and auditory displays in the Modified cockpit. During the initial GCAS alert (see Color Plate 4) all of the HDDs flashed red, and an auditory warning signal - a "doorbell" sound effect localized so that it appeared to emanate from the direction of the ground - was presented through the headphones. Simultaneously, a large arrow was superimposed on the HUD (see Color Plate 5), HMD, and center LCD of the HDD (see Color Plate 4) to indicate the vertical "up" direction as an aid in recovering the aircraft to an upright attitude. The vertical "up" arrow also included a pair of brackets that moved together at a rate proportional to the aircraft's closure rate with the ground. The brackets were calculated to meet at the center of the "up" arrow upon ground impact. After the initial four seconds of the GCAS alert, the HDD ceased to flash red and the "doorbell" audio warning signal was replaced with a "siren" sound effect that increased in both pitch and volume with decreasing height above the ground. All GCAS warning signals and displays were terminated as soon as the alert condition criteria were no longer met.



Color Plate 4. Ground Collision Avoidance System (GCAS) Alert Display.



Color Plate 5. GCAS Alert Display as it appeared on the Head-Up Display.

Threat Station Interfaces. The two enemy aircraft threat stations, consisting of a flight control stick, throttle, and 17" high resolution monitor, were equipped with two different visual interface modes. The first mode closely resembled the HUD display in the principal cockpit (see Figure 8), and was used to provide pilots with information regarding the status of numerous flight parameters, as well as navigation, radar, and weapons systems information. The second mode, or the cone-display, which is illustrated in Figure 9, consisted of a 2-dimensional planar depiction of the pilot's outside view. As can be seen in the figure, the bottom of the cone display represents the outline of the enemy aircraft's cockpit and the aircraft surfaces that would restrict the pilot's outside visibility. The center of the outline illustrates the fighter's instrument panel with a simplified HUD in the center. The W-shaped symbol on the HUD is a "waterline" symbol commonly used in aircraft attitude indicators to represent the aircraft. The center of the W represents the aircraft's longitudinal axis, around which the fighter rotates in a rolling maneuver at zero angle-of-attack and zero sideslip. The rest of the aircraft, canopy rail, wings, fuselage, vertical tail, etc., are depicted to the right and left of the center of the display. During the air-to-air combat trials, the entire aircraft outline remained fixed in the cone display, while the outside points moved about relative to it.

Procedure. Upon arrival to the Fusion Interfaces for Tactical Environments (FITE) laboratory, subjects received instructions as to the nature of their tasks. Each subject received approximately 16 hours of training and instruction during which they practiced flying the principal cockpit using both interfaces, and the enemy fighter threat station. Subjects were instructed that their primary task in the principal cockpit was to destroy the four enemy bombers and return to safe air space. Conversely, for trials in which they were assigned to one of the enemy fighter threat stations, subjects were instructed to protect the bombers and to destroy the principal cockpit. Each trial was interrupted twice to administer a situation awareness questionnaire to the subject in the principal cockpit. During these interruptions, the trial was halted and the dome display and the interfaces in the cockpit were "blanked." After completing the questionnaire, the trial resumed. In the event that the cockpit was killed before both situation awareness questionnaires were administered, the dome display and cockpit interfaces were "blanked" and the subject in the cockpit was instructed to fill out the remaining situation awareness questionnaire(s). Trials were terminated when the principal cockpit completed its primary task (i.e., destroyed the 4 bombers and returned to safe air space) or when the principal cockpit was destroyed. Following the completion of the experimental trials, subjects evaluated the Conventional and Modified interface conditions by completing a set of post-experimental questionnaires.

On-line measures of pilot-aircraft system performance were recorded throughout the entire experimental trial. The Situation Awareness (SA) questionnaire, which consisted of twelve questions, was randomly divided into two sets of questions (six each) for each experimental trial. These sets were administered at two randomly selected times

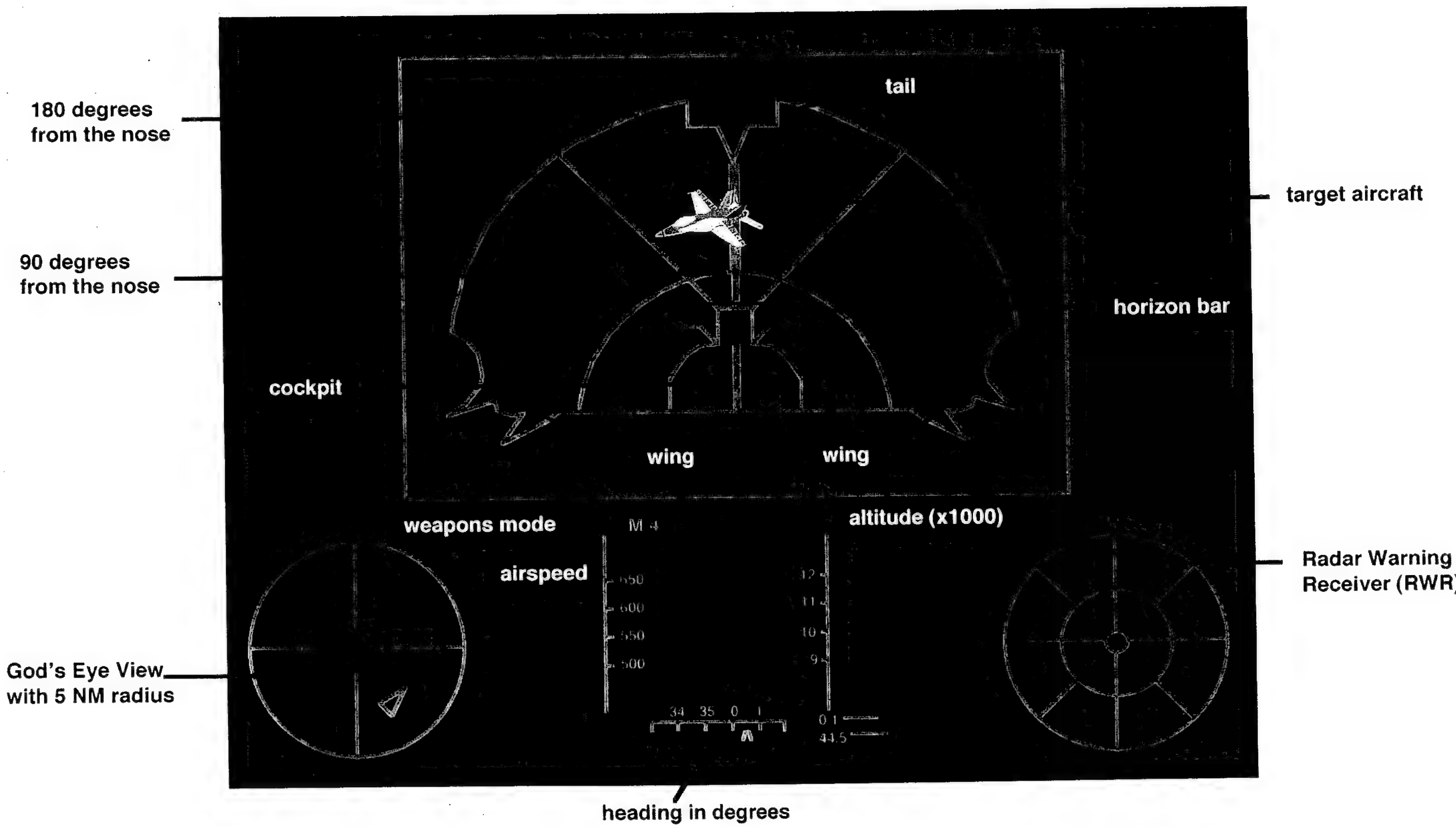


Figure 9. Threat Station Cone Display

during the experimental trial by interrupting the trials. The first interruption occurred between 30 and 150 seconds, and the second interruption took place between 210 and 330 seconds. The experimental trial resumed following the pilot's completion of the SA questions. The debriefing questionnaire was administered to all pilots following completion of the entire experiment.

5.3 Results

Fighter Performance. Because of limitations in the weapons models and on-line scoring measurement software implementation, all data related to the frequency with which pilots launched weapons that resulted in either a hit or missed target were obtained by observational scoring methods. Specifically, those pilots not involved as subjects in a given experimental trial served as scorers. The method used to determine a hit or miss was based upon similar methods used in fighter exercises such as Red Flag, that is, missile launches were directly observed by the scorers, and aircraft parameters such as altitude, speed, and bearing relative to the target aircraft were factored into the "hit" or "miss" decision.

Bombers Kills. Mean percentages of bombers killed by the principal cockpit in all experimental conditions are presented in Table 2. It is evident in the table that the percentage of bombers killed was slightly greater for the Modified interface (M = 68.75%) as compared to the Conventional interface condition (M = 65.62%). The data of Table 2 also indicate that the Medium Threat Altitude was associated with the highest percentage of bomber killed (M = 82.81 %) as compared to the High (M = 64.07 %) and Low (M = 54.68 %) Threat Altitudes. In addition, it can be seen in the table that in the case of the Low Threat Altitude, the percentage of bombers killed was greater in the Modified than in the Conventional interface condition, M = 59.37% and M = 50.01%, respectively.

Table 2
Mean Percentages of Bomber "Kills" in all Experimental Conditions

Interface Condition	Threat Altitude	Bombers Killed
Conventional	Low	50.01
	Medium	84.37
	High	62.50
Modified	Low	59.37
	Medium	81.25
	High	65.63

The data of Table 2 were subjected to a 2 (Interface Condition) X 3 (Threat Altitude) repeated-measures analysis of variance. The results of the analysis are presented in Table 3. As can be seen in Table 3, all sources of variances in the analysis lacked statistical significance. The absence of a significant main effect and/or interactions involving the interface condition factor implies that fighter performance, as measured by percentage of bombers killed, was equivalent for the Conventional and Modified interface conditions.

Table 3
Analysis of Variance For Percent Bomber "Kills."

SOURCE	DF	MS	F	P	G-G	H-F
interface condition	1	58.516	0.296	0.624	.	.
ERROR	3	197.578				
threat altitude	2	1640.313	1.322	0.335	0.336	0.336
ERROR	6	1241.250				
interface condition * threat altitude	2	78.047	0.147	0.866	0.771	0.831
ERROR	6	529.714				

Threats Kills. Table 4 presents the mean percentages of Threats (enemy fighters) killed by the principal cockpit in all experimental conditions. Overall, there was little difference in the percentages of Threats killed in the Conventional and Modified interface conditions, M = 13.54% and M = 14.59%, respectively. However, the percentage of Threats killed seemed to be highest for the Low Altitude (M = 18.75) as compared to Medium (M = 12.50) and High (M = 10.94) altitude conditions.

Table 4
Mean Percentages of Threat "Kills" in all Experimental Conditions

Interface Condition	Threat Altitude	Threat "Kills"
Conventional	Low	21.87
	Medium	12.50
	High	6.25
Modified	Low	15.63
	Medium	12.50
	High	15.63

The results of an analysis of variance of the percentages of Threats killed are summarized in Table 5. The analysis failed to reveal any significant sources of variance. Such a result indicates that fighter performance - percentage of Threat kills - was equivalent in both interface conditions.

Table 5
Analysis of Variance For Percent Threat "Kills."

SOURCE	DF	MS	F	P	G-G	H-F
interface condition	1	6.510	0.022	0.893	.	.
ERROR	3	301.649				
threat altitude	2	136.719	0.417	0.677	0.645	0.677
ERROR	6	327.691				
interface condition *threat altitude	2	123.698	2.280	0.183	0.221	0.208
ERROR	6	54.253				

Overall Outcomes (Win or Loss). A global assessment of fighter performance was made by recording the overall outcome of each trial, that is, whether or not the experimental trial resulted in a win or a loss. The former denoted trials in which all four bombers were killed and the principal cockpit returned to safe air space, whereas the latter referred to trials in which the principal cockpit failed to destroy all four bombers or did not return to safe air space. Presented in Table 6 are the per trial outcomes (win or loss) for all experimental conditions. It is important to note that although the data of Table 6 employs the same organizational scheme as the preceding tables (i.e. Tables 2, 4), parametric statistical tests were not performed on these data due to a lack of a sufficient number of observations.

It is evident in Table 6 that the frequency of "wins" for the Modified interface ($\Sigma = 8$) was higher than for the Conventional interface condition ($\Sigma = 6$). It can also be seen in Table 6 that in the Modified interface condition, the Medium threat altitude was associated with the highest number of "wins." In contrast, the Medium threat altitude produce the lowest number of "wins" in the Conventional interface.

Table 6
Trial Outcomes (win or loss) for all Experimental Conditions

Interface Condition	Threat Altitude	Trial Outcome Win	Trial Outcome Loss
Conventional	Low	2	6
	Medium	1	7
	High	3	5
Modified	Low	2	6
	Medium	4	4
	High	2	6
	Σ =	14	34

Ground Collisions and GCAS. Presented in Table 7 are the number of trials in which the principal cockpit suffered a ground collision. One characteristic that is immediately evident in the table is the absence of ground collisions in the Modified interface condition ($\Sigma = 0$). Conversely, the Conventional interface was associated with several ground collisions ($\Sigma = 3$). The absence of ground collisions in the Modified interface condition is probably due to the fact that it was equipped with a Ground Collision Avoidance System (GCAS), a visual-auditory signal, that warned pilots of an impending ground collision based on their current attitude and velocity. The Conventional interface condition was not equipped with GCAS.

Table 7
Number of Trials Resulting in a Ground Collision for all Experimental Conditions.

Interface Condition	Threat Altitude	Ground Collisions
Conventional	Low	0
	Medium	3
	High	0
Modified	Low	0
	Medium	0
	High	0

Table 8 presents the number of GCAS warnings that were presented in all experimental conditions. Because the Conventional interface condition was not actually equipped with a GCAS, the data in the table represent the number of times that the GCAS criteria were met in the Conventional interface condition. It is evident in the table that the number of GCAS alerts in the Modified condition ($\Sigma = 9$) was smaller than the Conventional interface condition ($\Sigma = 12$). Such a result indicates that the GCAS might be effective in minimizing the occurrence of dangerous or risky flight paths.

Table 8

Frequency of GCAS Alerts Issued for All Experimental Conditions.

Interface Condition	Threat Altitude	GCAS alerts
Conventional	Low	2
	Medium	4
	High	6
Modified	Low	6
	Medium	1
	High	2

Presented in Table 9 are the average recovery times from a GCAS alert for all experimental conditions. As noted earlier, the Conventional interface did not receive the GCAS alert; thus, in that condition the data of Table 9 refers to the length of time to recover from a flight path that would have activated the GCAS. As can be seen in the table, there was a dramatic difference between the Conventional and Modified conditions in the length of time to recover from a dangerous flight path, $M = 7.35$ sec and 2.11 sec, respectively.

Table 9

Average Time (sec) to Recover from a GCAS Alert for all Experimental Conditions

Interface Condition	Threat Altitude	Time (sec) to Recover
Conventional	Low	9.25
	Medium	6.33
	High	6.46
Modified	Low	1.69
	Medium	3.00
	High	1.63

In summary, the data of Tables 7- 9 indicate that the addition of the GCAS to the Modified interface resulted in (1) a decrease in the frequency of dangerous flight paths; (2) a dramatic reduction in the amount of time to recover from a dangerous flight path; (3) the elimination of ground collisions.

Friendly F-15 Kills. The frequency of friendly F-15 kills by the principal cockpit are displayed in Table 10 for all experimental conditions. Inspection of the table reveals that the Conventional interface resulted in three friendly F-15 kills. In contrast, there were zero friendly F-15 kills associated with the Modified interface condition.

Table 10
Frequency of Friendly - F-15 Kills in all Experimental Conditions

Interface Condition	Threat Altitude	Friendly F-15 Kills
Conventional	Low	0
	Medium	1
	High	2
Modified	Low	0
	Medium	0
	High	0

Situation Awareness. An overall situation awareness (SA) score was calculated for each trial by summing the correct responses to the SA questionnaire and converting these combined scores to percentages. Table 11 displays the mean overall SA scores for all experimental conditions. As can be seen in the table, the overall SA scores were approximately equal for the Conventional (51.39%) and Modified (53.47%) interface conditions. In addition, it is evident in the table that the low threat altitude produced the lowest SA scores (47.91%) as compared to the medium (53.12%) and high (56.25%) threat altitudes. An analysis of variance of the data of Table 11 is summarized in Table 12. No significant main effects or interactions were found for either of the two independent variables under investigation. Such a result indicates that SA, as measured by the SA questionnaire, was equivalent for the two interface conditions.

Table 11
Mean Overall Situation Awareness Scores for all Experimental Conditions

Interface Condition	Threat Altitude	SAQ Scores
Conventional	Low	45.83
	Medium	51.04
	High	57.29
Modified	Low	50.00
	Medium	55.21
	High	55.21

Table 12
Analysis of Variance for Overall Situation Awareness Scores

SOURCE	DF	MS	F	P	G-G	H-F
interface condition	1	26.042	0.529	0.519		
ERROR	3	49.190				
threat altitude	2	141.782	1.176	0.371	0.369	0.371
ERROR	6	120.563				
interface condition *threat altitude	2	26.042	0.818	0.485	0.457	0.485
ERROR	6	31.829				

Post Experimental Questionnaire. Upon completion of the experimental trials, subjects were asked to evaluate the Conventional and Modified interface conditions by completing a pair of post experimental questionnaires (see Appendices D and E). The questionnaire consisted of approximately 50 true or false, multiple choice, and fill-in-the-blank items that surveyed several general sub-tasks considered relevant to air-to-air combat performance. These sub-tasks included: target and threat identification, situation awareness, intercepts, close-in combat, egress, and maintenance of the CAP pattern. The results of the post experimental questionnaires are presented in the following section, and the questions are grouped according to the sub-task. The number in front of the question refers to the question number as it appeared on the questionnaire.

Target and Threat Identification

6. How long, on average, do you estimate it took to determine a target had met commit criteria, once that criteria had actually been met? ____ sec

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	10.000	5.000
MEAN	4.500	2.250
S.D.	4.041	1.893

7. Did you make any inaccurate commit decisions? Y/N If yes, how many?____

	Answer	Frequency
Conventional		
	no	2
	yes-3	1
	yes-6	1
Modified		
	no	3
	yes-2	1

16. What additional information did you require, or would have been helpful, for identifying friendly/hostile targets?

	Answer	Frequency
Conventional		
	none	1
	color code, faster NCTR	1
	faster NCTR	1
Modified		
	none	3
	increase detail	1

17. Did you ever attempt to intercept or engage a target in error? In other words, did you mistake a friendly for a threat, or a threat fighter for a bomber, etc.? Y/N If so, explain?

	Answer	Frequency
Conventional		
	no	2
	yes-F15	1
	yes-unknown	1
Modified		
	no	4

43. (39) Did you ever UNintentionally fire a weapon outside indicated permissible launch parameters? Y/N If so, explain?

	Answer	Frequency
Conventional		
	no	2
	yes	1
	yes-wrong PDT	1
Modified		
	no	4

44. (40) Did you ever INTENTIONALLY fire a weapon outside indicated permissible launch parameters? If so, explain.

	Answer	Frequency
Conventional		
	no	4
Modified		
	no	4

45. (41) What additional information did you require, or would have been helpful, for determining the location, status, and threat of hostile aircraft?

	Answer	Frequency
Conventional		
	gci/data link	1
	weapons	1
	quicker breakouts, color coding, larger target, range of radar, visual of commit	1
Modified		
	gci/data link	2
	better RWR, gci/data link, God's eye view	1
	none	1

The above results correspond with the finding that the modified cockpit resulted in fewer "friendly fire" incidents than the conventional cockpit. Pilots reported that identifications of aircraft were made more accurately and with greater speed using the modified cockpit, and that as a result fewer erroneous missile launches were made.

Situation Awareness

23. Did you experience any instances of loss of spatial awareness while performing a radar intercept? Y/N If so, would you categorize this event as minor, moderate, or serious?

	Answer	Frequency
Conventional		
	yes-minor	1
	yes-moderate	2
	yes-serious	1
Modified		
	no	1
	yes-moderate	2
	yes-serious	1

37. (35) Did you experience any instances of loss of spatial awareness while performing close-in combat? Y/N If so, would you categorize this event as minor, moderate, or serious?

	Answer	Frequency
Conventional		
	no	2
	yes-minor	1
	yes-moderate	1
Modified		
	no	3
	yes-moderate	1

48. (44) Were you shot down? Y/N If so, were you aware of the seriousness of the threat at the time? Y/N If not, explain.

	Answer	Frequency
Conventional		
	yes-no	4
Modified		
	yes-no	3
	yes-yes	1

These results indicate that pilots perceived no compelling differences between the two interface conditions in terms of the levels of situation awareness that each afforded. In this respect, these findings corroborate those obtained with the use of the situation awareness questionnaire.

GCAS (Modified condition only)

38. Were any GCAS alerts experienced during close-in combat? Y/N If so, were you aware of the critical nature of your flight conditions at the time? Y/N

Answer	Frequency
no	1

yes-no	2
yes-yes	1

39. What additional information did you require, or would have been helpful, for avoiding or recovering from critical low-altitude situations?

Answer	Frequency
none	3
better visual resolution	1

55. Were any GCAS alerts experienced during an egress? Y/N If so, were you aware of the critical nature of your flight condition at the time? Y/N

Answer	Frequency
no	1
yes-no	2
yes-yes	1

These results corroborate findings from other measures of performance indicating that pilots found the GCAS information provided in the modified cockpit to be useful. In two reported cases, pilots were not aware of the critical nature of their flight condition at the time a GCAS alert appeared.

Intercepts

11. On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining your position relative to a target during an intercept?

	Conventional	Modified
MINIMUM	2.000	1.000
MAXIMUM	5.000	4.000
MEAN	3.750	2.000
S.D.	1.500	1.414

12. On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining your threat from a target's weapon system during an intercept?

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	5.000	5.000
MEAN	2.500	3.000
S.D.	1.732	1.826

13. On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining the capability of your weapon system during an intercept?

	Conventional	Modified
MINIMUM	3.000	2.000
MAXIMUM	9.000	5.000
MEAN	5.000	3.000
S.D.	2.828	1.414

14. On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining your relative tactical advantage versus threats other than the primary target during an intercept?

	Conventional	Modified
MINIMUM	4.000	2.000
MAXIMUM	9.000	5.000
MEAN	6.500	3.250
S.D.	2.082	1.500

18. On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of remaining within prescribed airspace while performing radar intercepts?

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	5.000	2.000
MEAN	3.500	1.250
S.D.	1.732	0.500

19. Did you ever "spill-out" of prescribed airspace wile performing a radar intercept?

	Answer	Frequency
Conventional	no	3
	yes	1
Modified	no	1
	yes	3

20. On a scale from 1-100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while performing a radar intercept?

	Conventional	Modified
MINIMUM	15.000	50.000
MAXIMUM	80.000	80.000
MEAN	58.000	71.250
S.D.	26.599	14.361

21. On a scale from 1-100, what percentage of your available attention do you estimate was allocated to the task of searching for targets while performing a radar intercept?

	Conventional	Modified
MINIMUM	5.000	0.000
MAXIMUM	10.000	10.000
MEAN	7.500	5.000
S.D.	2.887	4.082

22. On a scale from 1-100, what percentage of your available attention do you estimate was allocated to the task of flying the aircraft (i.e. aircraft control, monitoring parameters, navigation, etc.) while performing a radar intercept?

	Conventional	Modified
MINIMUM	15.000	10.000
MAXIMUM	20.000	30.000
MEAN	18.750	18.750
S.D.	2.500	8.539

With several notable exceptions, pilots reported that the performance of tasks associated with the intercept phase of the mission were less demanding while using the Modified cockpit. A notable exception involved the high demands placed on attention while monitoring radar in the modified cockpit configuration. This finding suggests that this component of the display configuration should be improved to reduce these attentional demands.

Close-in Combat

27. (25) On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your position relative to your primary opponents during close-in combat?

	Conventional	Modified
MINIMUM	5.000	3.000
MAXIMUM	9.000	5.000
MEAN	7.000	4.250
S.D.	2.309	0.957

28. (26) On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your threat from an opponent's weapon system during close-in combat?

	Conventional	Modified
MINIMUM	4.000	2.000
MAXIMUM	9.000	6.000
MEAN	6.500	4.000
S.D.	2.380	1.826

29. (27) On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining the capability of your weapon system during close-in combat?

	Conventional	Modified
MINIMUM	4.000	1.000
MAXIMUM	5.000	5.000
MEAN	4.750	2.500
S.D.	0.500	1.732

30. (28) On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your relative tactical advantage versus your primary opponents during close-in combat?

	Conventional	Modified
MINIMUM	4.000	2.000
MAXIMUM	9.000	5.000
MEAN	6.000	3.750
S.D.	2.449	1.500

32. (30) On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of remaining within prescribed airspace while performing close-in combat?

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	2.000	4.000
MEAN	1.250	2.250
S.D.	0.500	1.258

33. (31) Did you ever "spill-out" of prescribed airspace while performing close-in combat?

	Answer	Frequency
Conventional	no	4
Modified	no	4

34. (32) On a scale from 1 - 100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while performing close-in combat?

	Conventional	Modified
MINIMUM	5.000	5.000
MAXIMUM	40.000	50.000
MEAN	21.250	22.500
S.D.	16.520	20.207

35. (33) On a scale of 1-100, what percentage of your available attention do you estimate was allocated to the task of visually searching for targets while performing close-in combat?

	Conventional	Modified
MINIMUM	20.000	10.000
MAXIMUM	90.000	90.000
MEAN	52.500	47.500
S.D.	28.723	33.040

36. (34) On a scale from 1-100, what percentage of your available attention do you estimate was allocated to the task of flying the aircraft (i.e., aircraft control, monitoring parameters, navigation, etc.) while performing close-in combat?

	Conventional	Modified
MINIMUM	10.000	5.000
MAXIMUM	40.000	75.000
MEAN	20.000	32.500
S.D.	14.142	32.275

40. (36) Did you ever lose control of the aircraft during close-in combat? That is, did the aircraft ever do something you did not intend or expect, were you ever below 100 KCAS, did you ever have to recover from a stall or spin, etc.? Y/N If so, explain

	Answer	Frequency
Conventional	no	4
Modified	no	4

41. (37) On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining permissible and optimum weapons launch parameters?

	Conventional	Modified
MINIMUM	2.000	1.000
MAXIMUM	9.000	5.000

MEAN	5.000	3.250
S.D.	2.944	2.062

49. (45) Were you always aware of the required response to any threat detected? Y/N If not, explain.

	Answer	Frequency
Conventional	yes	4
Modified	yes	4

These findings essentially replicate those obtained for the intercept phase of the air combat mission. With the exception of reporting greater difficulty in monitoring the radar display, pilots reported that tasks associated with the close-in portion of the mission were appreciably easier with the Modified cockpit configuration.

Egress

51.(47) On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining the most direct route to the safe area during egress?

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	2.000	5.000
MEAN	1.500	2.250
S.D.	0.577	1.893

52. (48) On a scale from 1-10, with 10 being "extremely difficult," how hard did you find the task of determining the threat level during egress?

	Conventional	Modified
MINIMUM	7.000	1.000
MAXIMUM	9.000	8.000
MEAN	8.250	5.000
S.D.	0.957	2.944

53. (49) Did you ever "spill-out" of a prescribed airspace during egress?

	Answer	Frequency
Conventional	no	3
Modified	no	4

54. (50) On a scale of 1-100, what percentage of your available attention do you estimate was allocated to the task of visually searching for targets while performing an egress?

	Conventional	Modified
MINIMUM	1.000	1.000
MAXIMUM	20.000	30.000
MEAN	8.250	14.000
S.D.	8.808	13.441

The findings for the egress portion of the air combat mission are somewhat more ambiguous than those for the previous two portions. Pilots reported somewhat greater difficulty in determining an egress route using the Modified cockpit, and also reported a higher percentage of attention required to visually search for targets in this condition. However, the task of determining threat level during this portion of the mission was reported to be easier with the use of the Modified cockpit.

CAP Pattern

1. On a scale of 1-100, what percentage of your available attention do you estimate was allocated to the task of maintaining the prescribed track in the CAP pattern?

	Conventional	Modified
MINIMUM	5.000	2.000
MAXIMUM	25.000	15.000
MEAN	13.750	6.000
S.D.	8.539	6.164

2. What do you estimate was your greatest deviation from the prescribed CAP pattern?
+/- ____ NM

	Conventional	Modified
MINIMUM	2.000	1.000
MAXIMUM	5.000	3.000
MEAN	3.000	1.750
S.D.	1.414	0.957

3. What do you estimate was your greatest deviation from the prescribed CAP airspeed? +/- ____ KCAS

	Conventional	Modified
MINIMUM	20.000	10.000
MAXIMUM	100.000	75.000
MEAN	61.250	47.500
S.D.	34.248	32.787

4. What do you estimate was your greatest deviation from the prescribed CAP altitude? +/- ____ FT

	Conventional	Modified
MINIMUM	1500.000	500.000
MAXIMUM	5000.000	5000.000
MEAN	2500.000	2125.000
S.D.	1683.251	2015.564

5. What additional information did you require, or would have been helpful, for maintaining prescribed CAP pattern track, airspeed, or altitude?

	Answer	Frequency
Conventional		
	God's eye view	1
	time to check	1
	none	2
Modified		
	CAP altitude	1
	Conventional CAP info	1
	none	2

9. On a scale of 1-100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while searching for targets in the CAP pattern?

	Conventional	Modified
MINIMUM	50.000	50.000
MAXIMUM	80.000	90.000
MEAN	70.000	73.750
S.D.	14.142	17.017

The results of questions concerning quality and ease of performance in maintaining the CAP pattern indicate a consistent advantage for the Modified cockpit condition. However, it was suggested that the addition of CAP altitude and other conventional CAP information would further enhance performance of this portion of the task.

5.4 Discussion

The results of this preliminary experimental evaluation indicate that comparable levels of air combat performance and situation awareness were obtained using a Modified fighter cockpit comprised of an array of multi-sensory, virtually-augmented displays, and a conventional array of fighter cockpit displays. While the finding of no differences between the two cockpit configurations might appear to be of little significance, it is important to consider the differences in training history for the two cockpit configurations. Pilots in the current study all had thousands of hours of training and experience with the Conventional cockpit interfaces. However, they had no previous experience with the Modified cockpit interfaces, and received very limited training on their use prior to data collection. This suggests that comparable levels of training on the two interface conditions could produce significantly higher levels of performance with the Modified cockpit.

In addition, notable advantages for the Modified cockpit were observed for two aspects of performance with high operational relevance - ground strikes and erroneous assaults on friendly aircraft. The latter finding is of particular interest in that in recent conflicts and exercises there has been significant loss of life associated with so-called "friendly fire" accidents. These accidents tend to occur in high workload, high stress situations where pilots are responding quickly to perceptual information that is too easily misinterpreted. Any reduction in the occurrence of such incidents that could be achieved through providing pilots with easily perceivable types of information concerning the identity of other aircraft would present a significant operational advantage. The results of

the current evaluation are encouraging in this regard, and suggest that further work should be conducted to optimize the presentation of this type of information.

Comments obtained from the debriefing questionnaire indicated that pilot acceptance of the Modified cockpit was high. Furthermore, questionnaire results tended to corroborate performance measures obtained during the experiment. For example, pilots reported that identification of other aircraft as friend or foe was performed with greater speed and accuracy using the Modified cockpit condition. This greater ease of identification is, in all probability, associated with the absence of "friendly fire" accidents in the Modified cockpit condition. In general, the majority of pilot remarks on the debriefing questionnaire indicated a strong preference for the Modified cockpit. Unfortunately, this preference did not translate into statistically reliable advantages in actual measures of performance. However, this is probably due to the limited number of observations that were made as part of this preliminary investigation. Future investigations will ensure adequate data samples are obtained to be sensitive to the existence of performance differences between interface configuration conditions.

Future work in the SIRE Laboratory related to the testing of virtual interface concepts for fighter aircraft applications will emphasize at least two factors: (1) expansion and refinement of the automated performance measurement system to eliminate potential reliability problems associated with the scoring of "hits" and "misses" using observational scoring methods, and (2) increasing the number of users who can participate in a given scenario to produce greater operational validity.

6.0 CONCLUSIONS

A program of research designed to develop and implement virtual interfaces in operational USAF systems is currently being pursued at the Armstrong Laboratory's Synthesized Immersion Research Environment (SIRE) Laboratory. While the current report has concentrated primarily on issues concerned with the development and use of virtual interfaces for fighter cockpit applications, the relevance of the SIRE Laboratory's research program extends into all applications of virtual environment technology.

Investigating human performance in complex tasks using virtual environments requires an experimental approach that takes adequate account of real-world task characteristics and associated measures of performance. A large portion of the work conducted in the SIRE Laboratory has been devoted to developing these aspects of the research program.

Our goal is to investigate the development of multi-sensory virtual interfaces to support performance of real-world tasks. The accomplishment of this goal will require research to be conducted on basic aspects of human perception and performance in virtual environments, as well as on applied aspects of human performance using prototype virtual environment systems. The experiment described in this report is an example of this latter type of research issue. Our findings, in this instance, indicated that comparable levels of performance can be obtained between conventional and modified cockpit configurations, the latter consisting of an array of multi-sensory, virtually-augmented interfaces. These findings are encouraging, particularly in light of the vast differences in training history associated with the use of the two configurations. Future work in the SIRE Laboratory dedicated to the development of virtual interfaces for fighter cockpits will build on the results of this preliminary work.

7.0 REFERENCES

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Appendix A. Order of Experimental Conditions

	Trial	Cockpit Interface	Threat Altitude
Subject 1	1	Conventional	Medium
	2	Conventional	Low
	3	Conventional	High
	4	Modified	Medium
	5	Modified	High
	6	Modified	Low
Subject 2	7	Modified	Medium
	8	Modified	High
	9	Modified	Low
	10	Conventional	High
	11	Conventional	Low
	12	Conventional	Medium
Subject 3	13	Conventional	Low
	14	Conventional	High
	15	Conventional	Medium
	16	Modified	High
	17	Modified	Medium
	18	Modified	Low
Subject 4	19	Modified	High
	20	Modified	Medium
	21	Modified	Low
	22	Conventional	Medium
	23	Conventional	High
	24	Conventional	Low
Subject 1	25	Modified	Low
	26	Modified	High
	27	Modified	Medium
	28	Conventional	Medium
	29	Conventional	Low
	30	Conventional	High
Subject 2	31	Conventional	Medium
	32	Conventional	Low
	33	Conventional	High
	34	Modified	Medium
	35	Modified	High
	36	Modified	Low

Appendix A (continued)

	Trial	Cockpit Interface	Threat Altitude
Subject 3	37	Modified	Low
	38	Modified	Medium
	39	Modified	High
	40	Conventional	Medium
	41	Conventional	High
	42	Conventional	Low
Subject 4	43	Conventional	Low
	44	Conventional	High
	44	Conventional	Medium
	45	Modified	High
	46	Modified	Medium
	47	Modified	Low

Appendix B. Measures of Fighter Performance.

1. 6 Degrees Of Freedom Position/Attitude data for each aircraft
2. Time and Target of each radar single-target track
3. Time and Target of each change in radar contact/Lock Status
4. Time and Target of each commit decision
5. calibrated airspeed
6. angle of attack
7. radar range selected
8. radar elevation bars selected
9. radar antenna elevation center selected
10. radar azimuth selected
11. radar mode selected
12. HMD position and orientation
13. weapons mode selected
14. weapons load
15. chaff/flare load
16. chaff/flare dispense command
17. time of each GCAS alert
18. number of GCAS alerts per trial
19. time and aircraft for all ground impacts
20. time of each visual detection (*) possibly from audio tapes
21. fuel state
22. time of commencing egress
23. time of "knock it off"
24. level of IR missile tone
25. roll rate (labeled left/right)
26. deviation from prescribed CAP pattern
27. Situation Awareness scores
28. outcome of each trial (Won, Lost)
29. number of Bombers Kills
30. number of Threat Station Kills
31. number of SRM Launched
32. number MRM Launched
33. number of SRM hits
34. number of MRM hits
35. number of rounds of gunfire
36. number of Friendly F-15 Kills
37. number of Ground Impacts
38. kill ratio

Appendix C. Situation Awareness Questionnaire

1. Please give the best answer of the choices provided. The bottom of my radar search coverage at ____NM is currently:

a) below ground level
b) ground - 5,000 ft MSL
c) 5,000-10,000 ft MSL
d) 10,000-15,000 ft MSL
e) above 15,000 ft MSL

2. The target aspect of the closest hostile contact is:

a) head-on (greater than 160 deg)
b) right flank (+/- 120-160 deg)
c) left flank (+/- 120-160 deg)
d) right beam (+/- 60-120 deg)
e) left beam (+/- 60-120 deg)
f) none of the above

3. The closest hostile contact is:

a) co-altitude (+/- 1,000 ft)
b) somewhat higher (+ 1,000-5,000 ft)
c) somewhat lower (- 1,000-5,000 ft)
d) significantly higher (greater than 5,000 ft)
e) significantly lower (greater than 5,000 ft)

4. The speed of the closest hostile target is:

a) co-speed (+/- 0.1 Mach)
b) somewhat faster (+ .2-.4 Mach)
c) somewhat slower (- .2-.4 Mach)
d) significantly faster (0.5 Mach or greater)
e) significantly slower (0.5 Mach or greater)

5. You are now within parameters to fire an available weapon at a hostile contact (assuming guidance requirements can be satisfied). True / False

6. You are now within prescribed airspace. True / False

7. You are now within threat weapons parameters. True / False

Appendix C. (continued)

8. There are currently how many hostile aircraft within your assigned threat sector?

a) none
b) 2
c) 4
d) 6
e) more than 6
f) none of the above

9. Your airspeed is now below corner. True / False

10. You now have an energy advantage over your nearest opponent. True / False

11. You are now out of MRMs. True / False

12. You are now within 1,000 lbs of JOKER fuel state. True / False

Appendix D. Post-experimental Questionnaire.

1. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of maintaining the prescribed track in the CAP pattern?

2. What do you estimate was your greatest deviation from the prescribed CAP pattern? +/-______NM

3. What do you estimate was your greatest deviation from the prescribed CAP airspeed? +/-______KCAS

4. What do you estimate was your greatest deviation from the prescribed CAP altitude? +/-______FT

5. What additional information did you require, or would have been helpful, for maintaining prescribed CAP pattern track, airspeed, or altitude?

6. How long, on average, do you estimate it took to determine a target had met commit criteria, once that criteria had actually been met? ______ SEC

7. Did you make any inaccurate commit decisions? Y/N If yes, how many? _____

8. What additional information did you require, or would have been helpful, for making the commit decision?

9. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while searching for targets in the CAP pattern?

10. What additional information did you require, or would have been helpful, for determining and controlling search volume in the CAP pattern?

11. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your position relative to a target during an intercept?

12. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your threat from a target's weapon system during an intercept?

13. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining the capability of your weapon system during an intercept?

14. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your relative tactical advantage versus threats other than the primary target during an intercept?

15. What additional information did you require, or would have been helpful, for performing radar intercepts?

16. What additional information did you require, or would have been helpful, for identifying friendly/hostile targets?

17. Did you ever attempt to intercept or engage a target in error? In other words, did you mistake a friendly for a threat, or a threat fighter for a bomber, etc.? Y/N If so, explain.

18. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of remaining within prescribed airspace while performing radar intercepts?

19. Did you ever "spill out" of prescribed airspace while performing a radar intercept?

20. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while performing a radar intercept?

21. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of visually searching for targets while performing a radar intercept?

22. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of flying the aircraft (i.e., aircraft control, monitoring parameters, navigation, etc.) while performing a radar intercept?

23. Did you experience any instances of loss of spatial awareness while performing a radar intercept? Y/N
If so, would you categorize this event as minor, moderate, or serious? Min/Mod/Ser

24. Were any GCAS alerts experienced during a radar intercept? Y/N
If so, were you aware of the critical nature of your flight condition at the time? Y/N

25. What additional information did you require, or would have been helpful, for obtaining radar locks during close-in combat?

26. Which CIC did you prefer during close-in combat?

Boresight (BST)
Vertical Scan Lock (VSL)
Slewable Scan Lock (SSL)
Helmet Mounted Display (HMD) (when available)
Why?

Appendix D. (continued)

27. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your position relative to your primary opponents during close-in combat?

28. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your threat from an opponent's weapon system during close-in combat?

29. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining the capability of your weapon system during close-in combat?

30. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining your relative tactical advantage versus your primary opponents during close-in combat?

31. What additional information did you require, or would have been helpful, for performing close-in combat?

32. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of remaining within prescribed airspace while performing close-in combat?

33. Did you ever "spill out" of prescribed airspace while performing close-in combat?

34. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of monitoring and controlling the radar while performing close-in combat?

35. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of visually searching for targets while performing close-in combat?

36. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of flying the aircraft (i.e., aircraft control, monitoring parameters, navigation, etc.) while performing close-in combat?

37. Did you experience any instances of loss of spatial awareness while performing close-in combat? Y/N If so, would you categorize this event as minor, moderate, or serious? Min/Mod/Ser

38. Were any GCAS alerts experienced during close-in combat? Y/N If so, were you aware of the critical nature of your flight condition at the time? Y/N

Appendix D. (continued)

39. What additional information did you require, or would have been helpful, for avoiding or recovering from critical low-altitude situations?

40. Did you ever lose control of the aircraft during close-in combat? That is, did the aircraft ever do something you did not intend or expect, were you ever below 100 KCAS, did you ever have to recover from a stall or spin, etc.? Y/N If so, explain.

41. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining permissible and optimum weapons launch parameters?

42. What additional information did you require, or would have been helpful, for determining permissible and optimum weapons launch parameters?

43. Did you ever UNintentionally fire a weapon outside indicated permissible launch parameters? Y/N
If so, explain.

44. Did you ever INTENTIONALLY fire a weapon outside indicated permissible launch parameters? Y/N If so, explain.

45. What additional information did you require, or would have been helpful, for determining the location, status, and threat of hostile aircraft?

46. Do you have any comments on the effectiveness of the defensive systems displays (i.e., RWR) for determining the location, status, and threat of hostile aircraft?

48. Were you shot down? Y/N If so, were you aware of the seriousness of the threat at the time? Y/N
If not, explain.

49. Were you always aware of the required response to any threat detected? Y/N
If not, explain.

50. What additional information did you require, or would have been helpful, for determining egress criteria?

51. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining the most direct route to the safe area during egress?

52. On a scale from 1 - 10, with 10 being "extremely difficult," how hard did you find the task of determining the threat level during egress?

53. Did you ever "spill out" of prescribed airspace during an egress?

Appendix D. (continued)

54. On a scale of 1 - 100, what percentage of your available attention do you estimate was allocated to the task of visually searching for targets while performing an egress?

55. Were any GCAS alerts experienced during an egress? Y/N If so, were you aware of the critical nature of your flight condition at the time? Y/N

56. What additional information did you require, or would have been helpful, for maintaining performing an egress?

57. Do you have any additional comments about anything not covered elsewhere in this questionnaire, including the simulations, facilities, scenarios, procedures, etc.?

Appendix E. Acronyms and Abbreviations

AAM	Air-to-Air Missile
ADI	Attitude Display Indicator
AMRAAM	Advanced Medium Range Air-to-Air Missile
AOA	Angle Of Attack
ARMs	Anti-Radiation Missiles
ATHS	Automatic Targeting Hand-off System
BDA	Battle Damage Assessment
BST	Boresight
BVR	Beyond-Visual-Range
CAP	Combat Air Patrol
CAS	Close Air Support
CIC	Close-In Combat
DCA	Defensive Counter-Air
deg	Degree
ECM	Electronic Countermeasures
EO	Electro-Optics
FITE	Fusion Interfaces for Tactical Environments
FLIR	Forward-Looking Infrared
FOR	Field Of Regard
FOV	Field-Of-View
ft	feet
GCAS	Ground Collision Avoidance System
GPS	Global Positioning System
HDD	Head-Down Display
HMD	Helmet-Mounted Display
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
IAMs	Inertially Aided Munitions
ID	Identification
INS	Inertial Navigation System
IPs	Initial Points
IR	Infrared
IRST	Infrared Search and Track
ISAR	Inverse Synthetic Aperture Radar
JTIDS	Joint Tactical Information Data System
KCAS	Knots Calibrated Air Speed
LADAR	Laser Radar
LANTIRN	Low Altitude Navigation and Targeting InfraRed for Night
lbs	pounds
LCDs	Liquid Crystal Displays
LDGP	Low Drag General Purpose
LGBs	Laser-Guided Bombs

LO	Low-Observability
LPI	Low Probability of Intercept
LRFs	Laser Range Finders
Mhz	Mega hertz
MMW	Millimeter-Wave Radar
MRF	Multi-Role Fighter
MRM	Medium Range Missiles
MSL	Mean Sea Level
MWS	Missile Warning Systems
NCTR	Non-Cooperative Target Recognition
NM	Nautical Mile
OTW	Out-The-Window Display
PD	Pulse-Doppler
PRF	Pulse-Repetition Frequency
RWR	Radar Warning Receivers
RWS	Range-While-Search
S.D.	Standard Deviation
SA	Situation Awareness
SAMs	Surface-to-Air Missiles
SAR	Synthetic Aperture Radar
SLAM	Stand-off Land Attack Missile
SRM	Short Range Missiles
SSI	Systems Status Indicator
SSL	Slewable Scan Lock
STT	Single-Target Track
TACAN	Tactical Air Navigation
TF/TA	Terrain-Following/Terrain Avoidance
TID	Target Identification System
TWS	Track-While-Scan
VSL	Vertical Scan Lock
VTOL	Vertical Takeoff And Landing

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